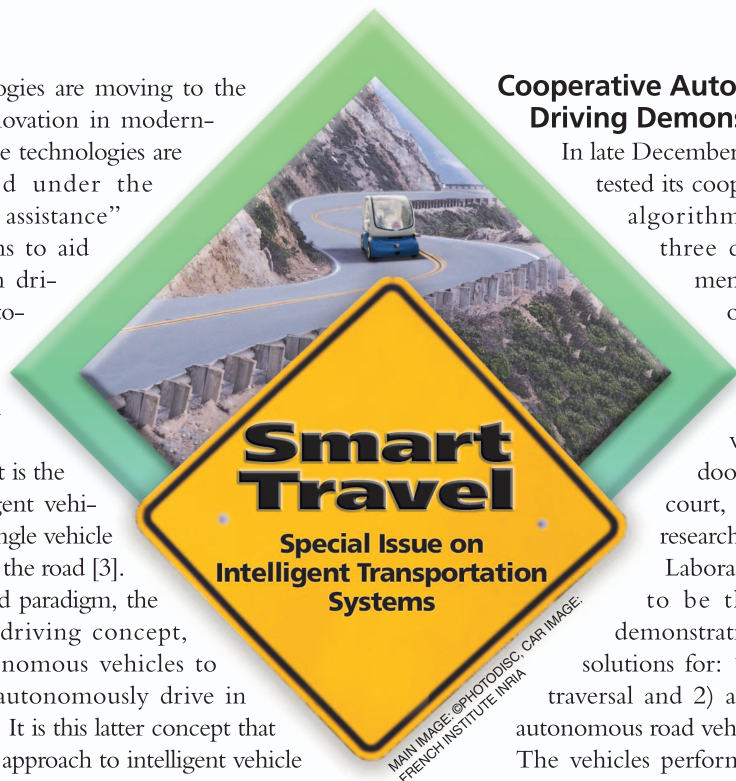
Cooperative Autonomous Driving

Intelligent Vehicles Sharing City Roads



Intelligent vehicle technologies are moving to the forefront of technical innovation in modern-day vehicles. Some of these technologies are already being deployed under the umbrella of the "driver assistance" concept. This concept aims to aid human beings with certain driving operations, such as automatic reverse parallel parking [1] or on-call autonomous driving based on a vision camera [2].

A more advanced concept is the autonomous driving/intelligent vehicle concept. This enables a single vehicle to drive independently along the road [3].

Finally, the most advanced paradigm, the cooperative autonomous driving concept, enables a plethora of autonomous vehicles to coexist on the roads and autonomously drive in cooperation with each other. It is this latter concept that is the focal point of one lab's approach to intelligent vehicle technologies. While several research groups are investigating cooperative autonomous driving in the context of the automated highway system, Griffith University's Intelligent Control Systems Laboratory (ICSL) distinguishes itself in two distinct ways: by developing solutions that operate in city environments and by emphasizing cooperative solutions to driving maneuvers that would enable autonomous vehicles to simultaneously coexist on the roads with vehicles driven by human beings.

Another distinguishing element of the ICSL's approach to intelligent vehicle technologies is that the algorithms currently enable vehicles to operate within the existing city infrastructure without the need for new road facilities. These algorithms operate primarily on information provided by onboard vehicle sensors.

Cooperative Autonomous Driving Demonstration

In late December 2002, the ICSL successfully tested its cooperative autonomous driving algorithms by deploying them on three computer-assisted experimental vehicle platforms developed by the French scientific organization INRIA and their industry partner ROBOSOFT. The tests were undertaken in an outdoor environment in Rocquencourt, France, in cooperation with researchers from INRIA's IMARA Laboratory. This event is believed to be the world's first on-road demonstration of cooperative driving solutions for: 1) unsignalized intersection traversal and 2) an overtaking maneuver by autonomous road vehicles designed for cities.

The vehicles performed several driving maneuvers in cooperation with each other and without any human assistance. The maneuvers included an unsignalized intersection traversal, a cooperative overtaking maneuver, a maneuver requiring the vehicles to drive one behind each other while maintaining distance and track control, and finally, a simple road-lane following behavior.

Figure 1 shows a picture of three experimental vehicles crossing an unsignalized intersection. The vehicles each cross the intersection in turn. They are able to successfully navigate the intersection without collision by cooperatively determining the order in which each vehicle traverses the intersection.

In Figure 2, the sequence of pictures shows the faster vehicle pulling out of the lane, moving alongside the slower vehicle, and finally overtaking the slower vehicle and resuming its

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Figure 1. *An experimental vehicle unsignalized-intersection traversal sequence.*

position in the original lane in front of the slower vehicle. This fulfills all the requirements of a cooperative overtaking maneuver; the slower vehicle reduces its speed from the moment it realizes that it is being overtaken and then resumes its speed after the overtaking maneuver is complete.

The success of the experimental vehicle demonstration is attributed to the earlier design, development, and testing of the ICSL cooperative autonomous driving maneuvers on the ICSL Cooperative Mobile Robot platforms, as shown in Figure 3.

In the following sections, we describe the deployment of the ICSL algorithms on INRIA's experimental vehicle platforms. We then explore the decision and control algorithms for cooperative autonomous driving maneuvers as developed by ICSL. Concluding remarks are then given.

The construct "intelligent vehicles" used within the remaining sections of this article relates to both the ICSL Cooperative Mobile Robot platforms and the experimental vehicle platforms because these platforms are manipulated by the same decision and control algorithms. Therefore, the term intelligent vehicle thus encompasses the concept of cooperative autonomous driving.

Deployment of ICSL Hardware/Software on Experimental Vehicle Platform

The demonstration was accomplished by interfacing ICSL's decision and control algorithms with INRIA's experimental vehicles. The two platforms communicate through the implementation of a CAN bus module on each system to standardize communications. This configuration is shown in Figure 4.

Once the communication link is established, the decision and control algorithms residing on ICSL's hardware determine the correct speed and steering angle of the vehicle. These values are sent to the vehicle's root processor and interpreted as commands to update the vehicle's speed and steering angle accordingly.

ICSL Platform

The ICSL hardware consists of a number of modules, as shown in Figure 5. Each microcontroller-based module is a node in the distributed architecture and represents a major functional component. The modules include

- decision and control modules
- motor-driving module
- sensor-interface module
- radio-communications module
- power-supply module

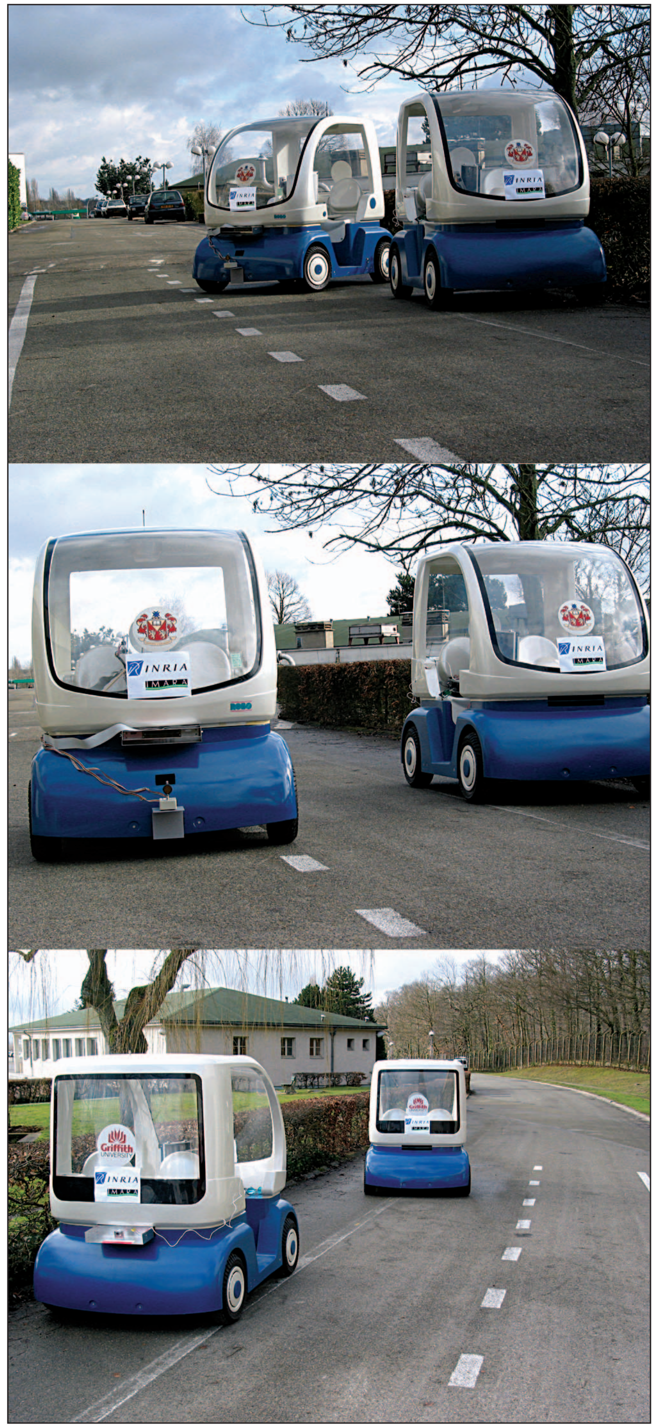

Figure 2. *An experimental vehicle cooperative-overtaking sequence.*

- sensor-carrier module
- distance- and tracking-control module.

Experimental Vehicle Platform

Figure 6 gives an architectural overview of the experimental vehicle platform developed by INRIA and its industry partner ROBOSOFT.

As shown in Figure 6, each wheel is surrounded by sufficient sensors to accurately determine the current speed and steering angle. The front wheels are controlled by a Motorola MPC555 microcontroller, and the rear wheels are controlled by a second Motorola MPC555 microcontroller. The two microcontrollers collaborate with a third x86-based embedded PC, called the *root processor*. The three controllers are interconnected via the CAN Bus 1 network.

The software for the vehicle was designed using Synchronized Distributed Executive (SynDEx), a design tool for rapidly prototyping and optimizing the implementation of real-time embedded applications on multiprocessor architectures [4]. SynDEx operates under the Algorithm Architecture Adequation (AAA) methodology. *Adequation* is a French word meaning an efficient matching, as opposed to *adequate*, which means a sufficient matching. The goal of the AAA methodology is to find the most efficient distribution of algorithms over a multiprocessor architecture [5].

Figure 3. *The ICSL cooperative mobile robots.*

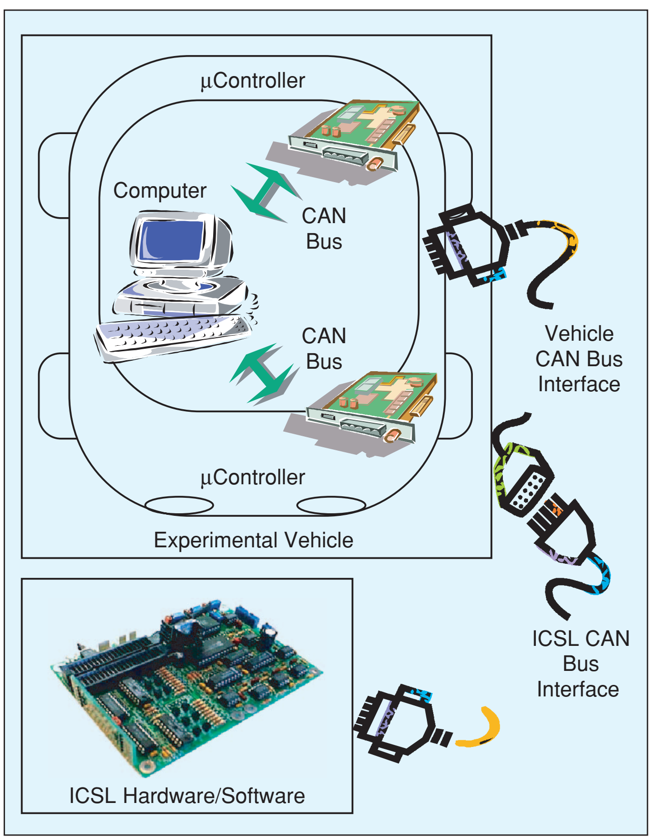

Figure 4. *The block scheme of interfacing the ICSL hardware with an experimental vehicle.*

Cooperative Autonomous Driving Maneuvers

The ICSL cooperative autonomous driving concept postulates that a number of autonomous vehicles may coexist on the road. In order to autonomously drive in cooperation with each other, share the driving environments with vehicles driven by human beings, and behave in a way that is compatible with vehicles driven by humans, intelligent vehicles ought to be [6]:

- autonomous
- computationally intelligent in order to
  - interact with the surrounding environment
  - cope with incomplete information
  - adapt to unpredictable changes within the surrounding road traffic network environment.

The following sections discuss the driving maneuvers that enable the intelligent vehicles to behave autonomously and cooperatively.

As space limitations do not allow us to elaborate on the original solutions designed for the ICSL cooperative mobile robots, the remaining sections of this article address only the most relevant driving maneuvers included in the ICSL cooperative autonomous driving concept. The details of the decision and control algorithms as well as the sensory subsystems may be found in ICSL papers published elsewhere.

Road-Lane Following

There are several motion control aims that must be fulfilled by intelligent vehicles performing road-lane following behavior

- Always more forward.
- Do not leave the lane boundary.
- Follow the lane direction as efficiently as possible.
- Avoid an obstacle that may be in the lane.
- Avoid being delayed by slower moving intelligent vehicles.

Figure 7 shows various corners and turns that intelligent vehicles may encounter when following a road. The solution to road-lane following behavior features the fusion of infrared and ultrasonic sensor data into a rule-based motion algorithm [7].

Cooperative Overtaking

The algorithm we developed fulfills the behavior requirements of intelligent vehicles operating in a real-world environment by enabling them to approach, identify, and overtake a slower moving object [7]. Since this is a cooperative algorithm, if the slower moving object is an intelligent vehicle, it will slow down further while being overtaken, facilitating the maneuver. This behavior is equivalent to the provision of an overtaking lane on a highway, where slower moving vehicles like heavily laden trucks may be overtaken. The overtaking maneuver is shown in Figure 8.

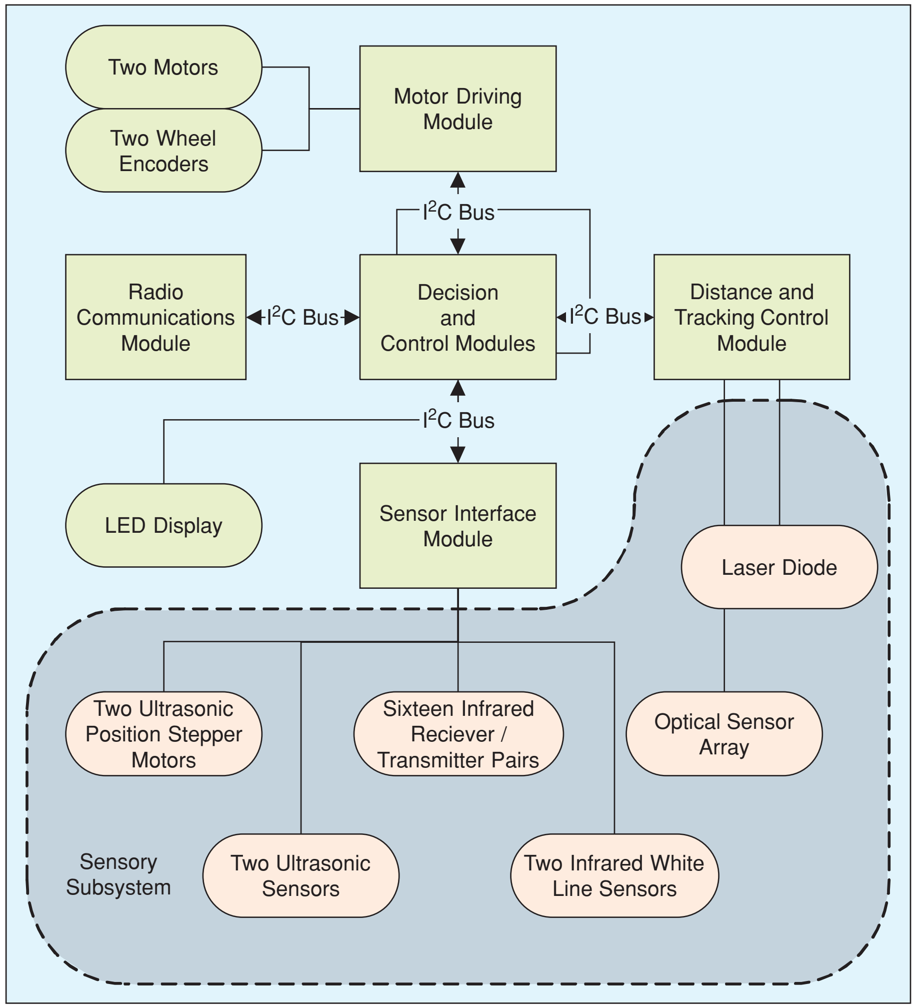

Figure 5. *The ICSL mobile robot architecture.*

Unsignalized Intersection

An unsignalized road intersection is where traffic flow is not governed by traffic lights, stop signs, or give-way signs. To successfully navigate an unsignalized intersection without collision, two or more intelligent vehicles must cooperatively determine the order in which they traverse the intersection [8].

The developed solution uses passive white lines to indicate the stopping positions and an event-driven decision-making algorithm to determine the order of intersection traversal. The algorithm precludes the possibility of the vehicles becoming deadlocked.

Distance and Tracking Control

The distance and tracking control (DTC) concept is the cooperative behavior of two successive vehicles traveling in the same direction in the same environment. This algorithm requires one vehicle (designated the leader) to move autonomously around its environment while another vehicle (designated the follower) maintains a coincident travel path and desired longitudinal distance with respect to the leader. The followers must perform DTC without any intervention from external supervisory systems or humans. A fuzzy controller is used to implement this algorithm [7].

The developed solution for the DTC problem has so far been effectively demonstrated in both a stop-and-go-motion driving maneuver (which is typical for city traffic-jam situations) and platooning (where a number of vehicles form a colony in forward motion).

Obstacle Avoidance

Intelligent vehicles must be able to navigate around their environment, avoiding collisions with other vehicles and other dynamic and static objects in that environment.

Typical approaches to the problem of obstacle avoidance often use either infrared or ultrasonic sensors but rarely use both. The combination of the two sensors overcomes any shortcomings of either sensor used individually and has shown significant capability when implemented in mobile robot-related applications. Each sensor complements the other to allow more robust obstacle-avoidance algorithms to be implemented.

Dynamic Obstacle-Avoidance Algorithm

The key limitation of the static obstacle-avoidance maneuver is that it cannot make intelligent navigation decisions in dynamic environments. To overcome this limitation, two components are necessary: 1) a sensor to determine the dynamics of the object and 2) a collision-avoidance scheme to utilize information from this sensor. We are currently testing a newly developed sensor that is able to segment the visual environment into coherently moving regions in real time while avoiding problems of temporal aliasing. This is achieved by processing a combination of visual and range information with an algorithm based on the optical flow constraint equation [9] embedded in a robust statistical

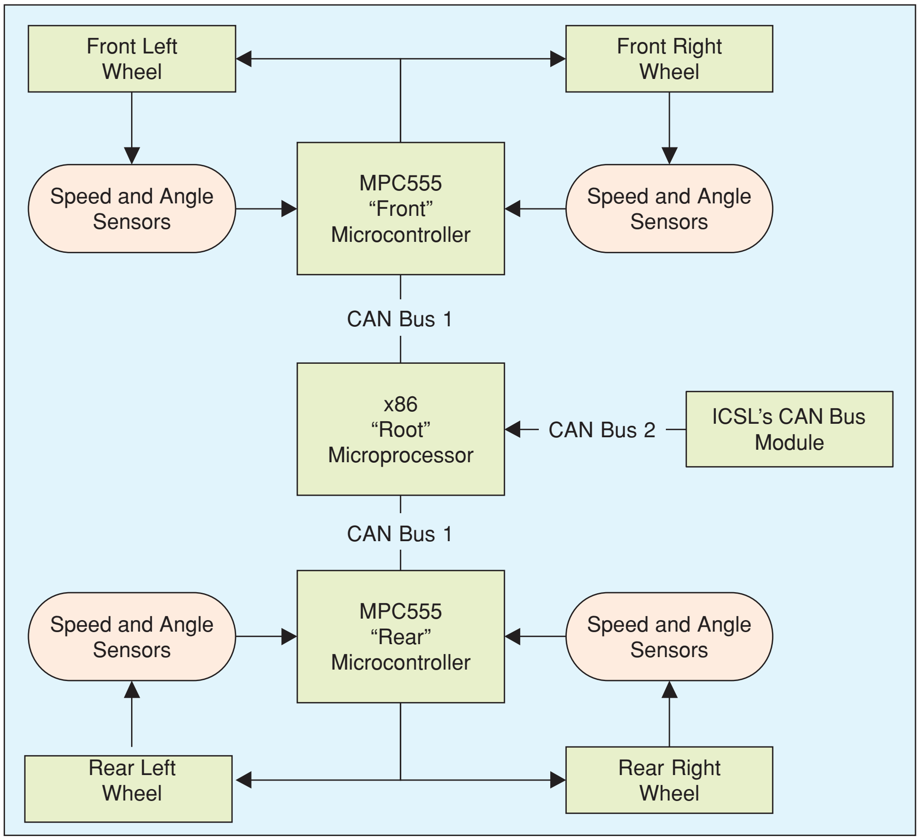

Figure 6. *The experimental vehicle architecture.*

framework. To ensure real-time performance with minimal size and power consumption, a single field-programmable gate array (FPGA) is used to implement both the algorithm and the interfaces and glue-logic components. The result is a compact intelligent sensor operating at 10 Hz that is able to deal with a wide range of apparent velocities [10].

Concluding Remarks

This article presented the ICSL's Cooperative Autonomous Mobile Robot technologies and their application to intelligent vehicles for cities. The deployed decision and control algorithms made the road-scaled vehicles capable of undertaking cooperative autonomous maneuvers.

The focus of the ICSL's research is in decision and control algorithms, not sensory input. It is therefore reasonable to consider replacing or upgrading the sensors used with more recent road sensory concepts as produced by other research groups, such as IBEO's ALASCA onboard sensor [11].

While substantial progress has been made, there are still some issues that need to be addressed such as: decision and control algorithms for navigating roundabouts, real-time integration of all data (data fusion), and decision-making algorithms to enable intelligent vehicles to choose the driving maneuver as they go (to perform that driving maneuver which is, as they believe, the most appropriate for the given traffic situation).

Regardless of the issues yet to be addressed, the results of this research on intelligent vehicle technologies have so far been extremely encouraging. With continued research, it is feasible that cooperative autonomous vehicles will coexist alongside human drivers in the not-too-distant future.

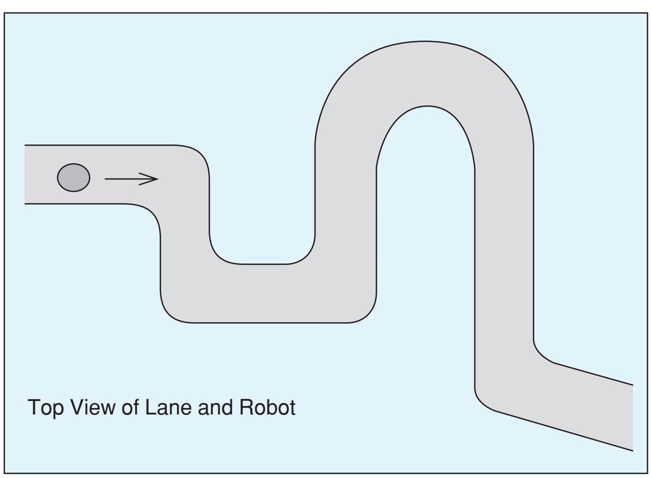

Figure 7. *A road-lane following maneuver.*

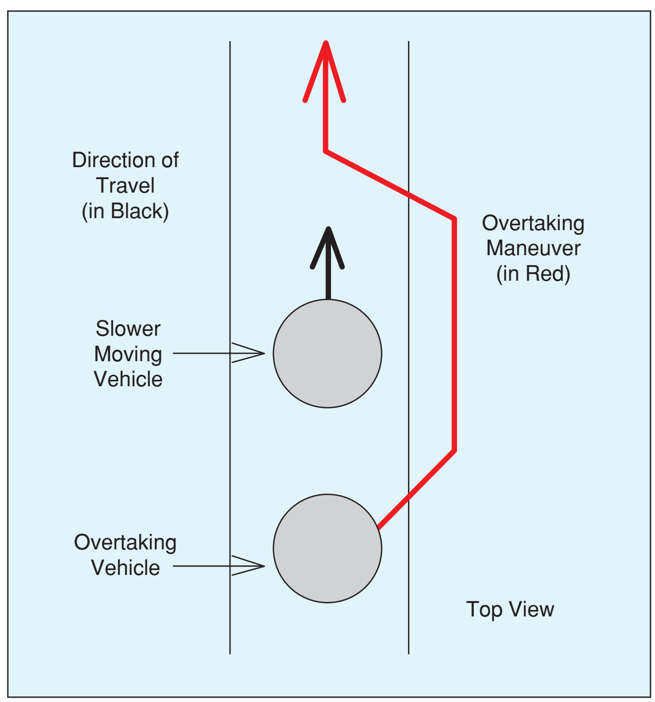

Figure 8. *An overtaking maneuver.*

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Keywords

Intelligent vehicles, cooperative autonomous driving, cooperative mobile robots, decision and control algorithms.

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