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Coding of Road Information for Automated Highways

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Abstract

Communication of information from the roadway infrastructure to vehicles is expected to enhance Automated Highway Systems (AHS) by supporting subsystem functions like vehicle motion control, multiple vehicle coordination, and vehicle navigation. A suitable communication channel is information coding in the lateral reference used for automatic steering and lane keeping control, e.g. in the magnet reference system used by California PATH (Partners for Advanced Transit and Highways). The presented coding strategy was designed for and tested at the I-15 test track near San Diego, CA, being prepared for the AHS demonstration of the National AHS Consortium (NAHSC) in 1997. A number of aspects are discussed, concerning types and structure of coded information, encoding and decoding schemes, and possible future extensions.

Keywords: Automated Highway Systems (AHS), Intelligent Vehicle and Highway Systems (IVHS), Intelligent Transport Systems (ITS), Advanced Vehicle Control Systems (AVCS), Lateral Reference System, Road Information Coding

1 Introduction

Highway automation is currently being investigated worldwide in several programs, e.g. in the US Intelligent Transportation Systems (ITS) program (see e.g. [1]) and similar programs in Japan [2], as a main subject of research and development of Advanced Vehicle Control Systems (AVCS). AVCS refers to the subclass of ITS aimed at increasing safety and throughput of road traffic while decreasing environmental impacts. A review of AVCS was presented by Shladover [3] and a possible scenario for an Automated Highway System (AHS) was outlined by Varaiya [4].

Within an AHS, several subtasks arise concerning the motion of individual vehicles (e.g. lateral and longitudinal vehicle control), coordination of multiple vehicles (e.g. vehicle platooning), and navigation of vehicles along a highway. Each of the subtasks requires a specific amount of information interchange (i.e. communication) between individual vehicles, between the roadway infrastructure and vehicles, and possibly also between vehicles and the roadway infrastructure. This paper concentrates on unidirectional communication from infrastructure in the roadway to individual vehicles via coding in the lateral reference system used for lane keeping control.

In the AHS scenario presently studied at California PATH [5], magnetic markers are used as references for lane keeping control [6]. The magnets are implanted in the road surface and measurements of vehicle lateral displacement from the magnets are used to automatically steer vehicles within the designated lane. Furthermore, magnetic markers are an excellent provision for binary coding using their polarity. Binary coding allows to transmit information from the roadway to the vehicle to be utilized in all AHS subtasks. Similarly, human driving behavior features information communication from the roadway to the driver. In particular, human drivers extract and exploit both explicit road information such as roadside signs, and implicit road information like upcoming road geometry during highway driving [7].

This paper discusses the various issues related to code design for AHS such as the type of information about highway features to be communicated, information distribution, codeword structure, and encoding and decoding strategies. The main goal is to share the experiences gained in designing the code for the test track prepared for the National Automated Highway Systems Consortium (NAHSC) demonstration on I-15 near San Diego, CA, scheduled for August 1997. Future possible implementations of AHS can build on these experiences and will extend the coding methods described here in an effort to accommodate the specifics of the respective highway. Hence, when designing the code for the I-15 test track, an attempt was made to yield high generality, allowing incorporation of a number of possible extensions.

AHS Subtask Information	Vehicle motion control	Multiple vehicle coordination	Vehicle high- way navigation
Road geometry (curvature)	X		
Reference system (magnet type)	X		
Merge/diverge ramps	X	X	X
Lane change	X	X	
Highway/lane/ramp ID		X	X
Milepost (Kilometerpost)			X

Table 1: Information features and benefiting AHS subsystems

2 Feature Selection

The AHS subtasks “vehicle motion control”, “multiple vehicle coordination”, and “vehicle highway navigation” are significantly enhanced by communication of a selection of information about highway features from the roadway infrastructure to each individual vehicle. A set of possible features is shown in Table 1

The following subsections discuss the different types of information to be coded in the magnet markers used as a lateral reference system, detailing the information content. Depending on the type of information, ‘transition coding’ or ‘total length coding’ was employed. Information about features which change at arbitrary locations and persist for an indefinite length was coded before each transition occurs. Features with distinct lengths were coded with their total length rather than with two transition codewords at the start and the end, respectively. The coding for a feature also contains the desired distance between the location of the codeword on the roadway and the actual location where the contained information takes effect.

2.1 Road Geometry (Curvature)

Communicating road geometry to the vehicle motion control system improves safety and ride comfort. Vehicle motion control comprises the so called “low level” driving tasks longitudinal and lateral control. Longitudinal control is responsible for maintaining proper spacing between individual vehicles and is independent of roadway specifics for most AHS scenarios. Lateral control is used to automatically steer individual vehicles within the designated lane. A reference marker system such as the magnetic markers employed in the California PATH Program [5] delineates the center of the lane [6, 7]. Magnetometers mounted on the vehicle,

usually at the front bumper, detect the lateral displacement from the reference and allow the lateral control system to calculate a steering command within a feedback control loop.

The lateral displacement is measured at a location directly below the magnetometers at the front bumper, hence magnetic markers fall into the category of “look-down” reference systems. Automatic steering feedback control design is one of the most challenging control tasks within AHS and is significantly improved by preview of the upcoming road curvature, i.e. for utilization as feedforward control. This also improves ride quality, since US highways feature abrupt curvature changes without clothoid transitions as are being used in Europe. Preview of upcoming curves allows lateral control to generate smooth transitions using anticipatory behavior via appropriate preparation for entering a curve, rather than purely reactive behavior without prior knowledge of road geometry, which would result in lateral jerks at curve beginnings and ends.

In order for the lateral control system to generate a smooth transition into or out of a curve, changes in road curvature should be previewed by approximately 20 m. This allows to create a virtual clothoid transition in the lateral control software within the system reaction time. The information to be communicated to the vehicle via magnetic marker coding henceforth consists of the actual upcoming road curvature, the direction of the curve (left or right turn), and the exact starting location of a curve. The end of a curve is marked with a similar code, describing the transition to zero curvature for a straight line segment or to another subsequent curve.

2.2 Reference System (Magnet Type)

Different lateral reference systems may be used in future AHS implementations. Changes within one single reference system or changes of the reference system itself have to be communicated to AHS vehicles. For the NAHSC test track in San Diego, CA, the magnetic marker system [6, 7] was selected, using two different types of magnets. The advantages of magnetic markers include their reliability and independence of weather conditions, ease of maintenance due to being passive rather than active markers, and the ability to incorporate information coding as described in this paper.

Ceramic magnets are being used on normal concrete pavement of I-15, while *rare earth* magnets have been selected for bridge structures. Rare earth magnets are more expensive, but considerably stronger than ceramic magnets, which allows to use 2.5 cm long magnets as compared to 10 cm long ceramic magnets. On bridge structures, drilling 10 cm deep magnet holes at locations specified with high accuracy proved hazardous with respect to the structural integrity of the bridge and shorter rare earth magnets are being employed.

Sensing and signal processing for detection of lateral vehicle displacement from the reference uses a mapping of the magnetic field of single magnets and hence depends on knowledge of the magnet type currently utilized on a certain stretch of road. The start of a bridge struc-

ture can be marked just before the transition takes place; no prior “warning” is necessary for switching between magnet mappings used in signal processing. Since ceramic magnets are defaults and bridge structures are relatively short, information about bridge structures is given in terms of the total number of consecutive rare earth magnets to be found, requiring just one codeword at the beginning of a bridge. An alternative would be to use separate codewords for marking transitions between magnet types, as employed for coding curvature changes. However, transition coding requires two codewords for each bridge, one for switching from default ceramic magnets to rare earth magnets, and one for switching back to default ceramic magnets. Coding transitions between magnet types may be useful, however, if long stretches of non-default magnets, if more than two magnet types are used, or if several types of different reference systems other than magnets are employed.

2.3 Merge/Diverge onto/off Ramps

At on-ramps, a lane merges into a through lane. Conversely, at off-ramps, a lane diverges off a through lane and leads onto a ramp. In addition, lanes may be added or dropped alongside the main lanes, which also creates diverge and merge situations, respectively. The reference path of a merging lane, delineated by the magnetic markers, terminates when the two lane centerlines approach within 0.9 m (approx. 3 *ft*) to avoid interference of magnetic fields of adjacent magnets, see also Figure 1. Lane diverges are constructed respectively, with the magnet reference of the diverging lane commencing with a lateral offset of 0.9 m from the through lane.

Information about up-coming merges and diverges comprises identification of highway lane/ramp into which a merge takes place, or identification of the ramp the diverging lane branches onto, the direction of merge/diverge (left or right) and the merge/diverge angle α between the lanes, see Figure 1. For the I-15 NAHSC test track, merge/diverge angle information and lane/ramp identification were comprised into a single ID since only few merges and diverges occur. Merge/diverge information should be communicated to vehicles at least 60-80 m before the start/end of a lane/ramp, to allow proper preparation of the lateral control system for a smooth transition.

In particular, an increasing artificial offset is added to the lateral displacement measurements before a merge/diverge, directing the vehicle towards the new magnet reference line ahead of the actual transition. The PATH sensor system consists of three magnetometers in each bumper, one in the center plus two at a lateral offset of ± 30 cm. This configuration yields a total sensor range close to 1 m for front and rear bumper lateral displacement measurements. Utilization of three magnetometers also allows to simultaneously detect two adjacent magnet reference lines for a short transition period, the through lane reference and the merging/diverging lane/ramp reference, yielding a smooth transition between the lanes.

Merge/diverge information is also used both for the coordination of multiple vehicles and

for navigation purposes. Hence, an additional 80-100 m preview distance before lane/ramp starts/ends was provided on the I-15 test track, to allow for communication between vehicles and navigators, which usually operate on larger time scales than low level controllers. For example, if a vehicle is to be integrated into a platoon directly at the entrance, the respective speeds have to be coordinated. The current total preview distance of 160-180 m could be further increased for AHS implementations, depending on the operation scenario.

Figure 1: Merge and diverge situations on two throughlanes of a highway with two ramps at angles α_1 and α_2

2.4 Lane change

AHS requires the ability of single vehicles and possibly of groups of vehicles, e.g. vehicle platoons, to change lanes on multiple lane highways for traffic coordination, at intersections and at AHS entrances and exits. Lane change of vehicles can be performed either with or without infrastructure guidance. Infrastructure guided lane change uses an additional line of lateral reference markers for connecting two adjacent highway lanes. The connecting lane starts with reference magnets at a lateral distance of 0.9 m from the through lane, crosses the lane boundary along a straight line and terminates 0.9 m away from the target through lane. The diverge from the initial through lane onto the guiding connecting lane and the merge into the target through lane are similar to merge/diverge operations for ramps and hence are treated as described in Section 2.3. Three infrastructure-guided lane changes were implemented on I-15, for an example see Figure 2 (a).

Free lane change without infrastructure guidance requires the vehicle to leave the magnet reference line, to cross over into the target lane using dead-reckoning, and to resume magnet

tracking upon reaching the magnet reference line in the target lane. The crossover trajectory is usually defined as an S-curve with smooth curvature transitions to avoid lateral jerks, see Figure 2 (b). Dead-reckoning between the two lanes uses measurement of vehicle yaw rate and lateral acceleration to estimate the lateral distance the vehicle has departed from the original lane while following the S-curve trajectory. However, since vehicle motion measurements are corrupted by noise and disturbances/biases like road super-elevation, free lane change based on dead-reckoning is restricted to areas with predictable road characteristics during normal AHS operation.

In particular, sufficiently long stretches with constant road geometry (constant curvature, super-elevation etc.) were chosen as potential free-lane-change areas. Among and within the free-lane-change areas, regions were selected such that no other codeword on either lane would be missed during a free lane change while the vehicle is away from magnetic markers. Information about free lane changes is communicated to the vehicles at the start of a region, specifying the total length of permitted free lane change with an appropriate resolution. The ‘total length’ coding was preferred over the ‘transition’ coding with one codeword at the beginning and one codeword at the end of a free-lane-change region since the codeword marking the end may be missed if the vehicle was performing a free lane change at this point.

Figure 2: Lane change scenarios for AHS roadways

2.5 Highway/Lane/Ramp Identification

This code identifies highway lanes and ramps to AHS vehicles for navigation purposes, possibly in conjunction with a Global Positioning System (GPS). Lane and ramp information is

also useful for coordination of vehicles, e.g. for lane change maneuvers as described above. Since storage devices are relatively inexpensive, identification coding can furthermore be utilized to extract additional highway information from stored maps or data files, e.g. travel information such as speed limits.

For the I-15 test track, a simplified numbering scheme was employed to identify lanes and ramps. A two-digit decimal number was assigned to each lane/ramp, also distinguishing the respective ID location at the South/North end of the test track. For future implementations, code information is likely to contain the full ID of the highway, comprising interstate or state highway number, lane designation, direction of travel, and additional navigation information for ramps.

2.6 Mile-post (Kilometer-post)

Mile-posts or kilometer-posts are also used mainly for navigation purposes. Combined with counting of magnet markers along the roadway, the accurate locations on the highway can be derived at any time. For example, the approach of a highway intersection or of the final destination of an AHS vehicle can be monitored and appropriate exiting action can be initiated: The exiting vehicle is extracted from its current group of vehicles, e.g. a platoon, isolated on the lane the exiting ramp diverges from, and prepared for exiting. If the vehicle continues on another highway, merging into the target highway is subsequently commanded. For vehicles having reached their final AHS destination, the driver is prepared for resuming manual control of the vehicle in an appropriate manner at the exit ramp.

Furthermore, in conjunction with stored highway maps and data files, mile-posts or kilometer-posts can be exploited for supplementary travel information and for redundancy of other coded information. This would allow flexible information transmission by frequently up-dating maps and data files, similar to, but with more detail than highway lane and ramp identification coding.

2.7 Possible Extensions to Information Coding

A number of extensions of the above information coding were discussed during preparation of the I-15 test track. One set of possible extensions comprises additional road geometry information, another set is concerned with general road and travel data (e.g. "yellow pages"). Since vehicle motion control is the subject of on-going research, the extent of road geometry information besides road curvature required for AHS has not yet been fully determined. For example, super-elevation information might be necessary for automatic steering control, or slope information may be needed for longitudinal control.

For multiple vehicle coordination and for highway navigation, road specific information

could be incorporated into the coding. Typical examples are speed limits for certain stretches of the highway. However, for future AHS implementations, such information should be categorized into “permanent” and “variable” information. Permanent information, e.g. curvatures, can be “hard-coded” into the highway using magnet binary coding, very similar to conventional roadside signs and painted markings. Variable information such as temporary speed limits can also be “soft-coded” by using permanent codes like highway identifications or mile-posts as placeholders for more specific information stored in maps and data files. Such maps and data files about highways could be up-dated frequently, or even transmitted to the vehicle on-line upon entry of AHS. Electronic variable message signs are nowadays’ equivalents of future information soft-coding.

3 Information and Codeword Structure

This section discusses the structure of the information coded into the magnetic markers. Each feature information is comprised in one codeword, consisting of four parts: an “attention sequence”, a “header”, a “main body”, and a “trailing sequence”. Prior to describing the structure of each part, the specifics of the coding on the NAHSC test track are summarized, some of which complicate matters beyond what is to be expected on “normal” AHS lanes. The effects of the I-15 test track peculiarities on future AHS implementations are further discussed in Section 5.

For redundancy and fault tolerance in the actual codeword, a 4/7-Hamming code was selected, encoding 4 information bits into 7 code bits. The 4/7-Hamming code allows to detect and to correct single bit errors in the 7 code bits. Multiple bit errors within 7 code bits can neither be corrected nor detected. The 4/7-Hamming code with single bit error correction capability was selected based on experiences of error probabilities gained at California PATH [5] over almost a decade with several test tracks. On one hand, the 4/7 Hamming coding enables having flexible length codewords with a good, 4 bit resolution, as compared to an 8 bit resolution e.g. of an 8/13-Hamming code. On the other hand, the ability of correcting 1 bits errors within 7 code bits proved sufficient, even though currently, both magnet polarity misreadings and errors in manual magnet installation have to be corrected.

In future AHS implementations, magnet installation will be automated to reduce magnet installation errors, possibly leading to coding schemes with less redundancy. On the I15 test track, the magnet polarity was checked using a cart equipped with magnetometers and a computer system to obtain an error-free coding. Furthermore, no magnet polarity misreading occurred during extensive experimentation at PATH within the last five years.

3.1 Specifics of I-15 Test Track

The NAHSC test track is a stretch of I-15 near San Diego, CA, and comprises approx. 8 miles of two HOV lanes between the I-15 intersections with Route 163 (southern end) and Route 56 (northern end). The two HOV lanes are separated from the regular I-15 lanes by concrete barriers and entering/exiting is only possible at either end. During normal operation, the two HOV lanes are open for rush hour traffic, southbound in the morning hours and northbound in the afternoon. Since contrary to most highways, the lanes are being used bidirectionally, information coding was designed such that the NAHSC demonstration is feasible both in southbound and northbound directions.

Bidirectional usage of highway lanes and ramps significantly increases the complexity of information coding. First, information is to be categorized into “unidirectional” and “bidirectional” features. Unidirectional codewords contain feature information useful to the vehicle only when traveling in one distinct direction (e.g. southbound), but not in the other direction (e.g. northbound). Examples are up-coming road geometry, merge/diverge, bridge structures, and lane change permits. Bidirectionally coded information is utilized by the vehicles when traveling in either direction, e.g. highway lane and ramp identification, and mile-posts/kilometer-posts.

For unidirectional coding, provision has to be undertaken to prevent reading and interpreting the codeword when traveling in the “wrong” direction. Furthermore, for each feature, e.g. a curvature change, two codewords are required, one for each traveling direction. Bidirectional coding, on the other hand, requires specification of the intended code reading direction and one codeword suffices for both directions.

3.2 Attention Sequence

The purpose of the attention sequence is to both trigger and synchronize the decoding scheme when traveling along an AHS roadway. Furthermore, the direction of codeword reading and interpretation has to be specified to accommodate bidirectional travel as described above.

Redundancy in the attention sequence is vital for successful decoding. Unless decoding is properly synchronized at the beginning of a codeword, decoding may not be able to extract the contained information. A moving 4/7-Hamming window was selected for triggering the decoding scheme. Among the 16 possible codes of the 4 information bits, exactly two codes possess unique synchronizing capabilities and were selected for the attention sequence. Assuming that the last seven bits before an attention sequence are defaults, none of the seven shifted approach windows of 7 trigger bits decode into the synchronizing 4 information bits of the attention sequence, even if one bit is toggled. In other words, no combination of n default bits and m attention sequence bits, with $n = 7, 6, \dots, 1$, $m = 0, 1, \dots, 6$, and $n + m = 7$ decodes into the synchronizing 4 information bits with a redundancy of one

Step	Shifted approach window	Trigger
-7	11111111xxx	-
-6	1111111x xxx	-
-5	111111xx xxx	-
-4	11111xxx xxx	-
-3	1111xxxx xxx	-
-2	111xxxxx xxy	-
-1	111xxxxxx xyy	-
0	111xxxxxxxx yyy	yes

Table 2: Moving 4/7 Hamming window for synchronization of decoding (‘1’: default bit, ‘x’: placeholder for 7 bit trigger code in the attention/trailer sequence, ‘y’: placeholder for 3 direction bits in the attention/trailer sequence; boxed bits are decoded, any single one of them may be toggled)

bit. In Table 2, the bits of the seven shifted approach windows are marked by a box and the approach steps are numbered -7 to -1. Decoding is only triggered at step 0, when the approach window coincides with the seven trigger bits, delineated by ‘x’.

In addition to triggering the decoding scheme, the attention sequence should contain the direction of intended decoding to allow bidirectional code. For increased redundancy, a 2-out-of-3 bit voting scheme was designed for this purpose. The first 3 bits immediately after the 7 trigger bits are either all zeros or all ones (placeholder ‘y’ in Table 2). Two or more zeros indicate forward reading, two or more ones indicate backward reading. Forward reading and interpretation uses a ‘first-in-first-out’ (FIFO) structure, whereas backward reading and interpretation reverses the code by using a ‘last-in-first-out’ (LIFO) stack, see also Section 4.2.

3.3 Code Header

The header contains the codeword identification, the type of the code to follow (e.g. road geometry), and indication of the actual starting location of the embodied information. The codeword ID is a unique number and serves as an additional source of redundancy as well as a source of flexibility for code interpretation. On one hand, a look-up table could be used to verify the information contained in the main body of the codeword by matching it with the code ID. Verification of read information via a look-up table provide a second degree of redundancy other than the redundancy in the 4/7-Hamming code for cases of multiple

magnet misreadings. On the other hand, flexibility in assigning multiple meanings to codes is achieved, leading to a to obtain soft-coding capability as discussed in Section 2.7.

The code type specifies the code interpretation, i.e. whether the main body should be decoded as a curvature code, a bridge code etc. In order to accommodate different desired starting locations of the actual feature information prescribed by the codeword, the header also contains a ‘starting point indicator’.

Header (and main body) of each codeword are encoded using the 4/7-Hamming code for redundancy. The structure and length of the header is similar for all code types to provide uniformity in decoding. Only the main body varies between code types as discussed below.

3.4 Main Body of Code

The main body contains the actual feature information of the codeword. Since different code types require different amounts of information to be coded, the length of the main body varies. The following list details the main bodies of the six code types discussed in Section 2.

1. **Road geometry (curvature).** Absolute value of up-coming road curvature in $[1/m]$ with pre-set resolution and direction (left or right turn).
2. **Reference system (magnet type).** Absolute number of rare earth magnets on a bridge structure.
3. **Merge/diverge.** Differentiation between merge and diverge; direction (left or right); ID of lane/ramp merging or diverging occurs to.
4. **Lane change permit.** Length of stretch of permitted free lane change.
5. **Highway ID.** Identifying number assigned to each lane and location (South/North end).
6. **Kilometer-post.** Absolute kilometer-post in $[km]$ according to survey stationing.

3.5 Code Trailer

The trailing sequence is the inverse of the attention sequence. First, a 2-out-of-3 voting specifies the code reading direction, opposite to the attention sequence. Second, the 7 trigger bits are repeated in inverse order to allow synchronization for bidirectional reading when traveling in opposite direction. When encountering a unidirectional code in opposite direction, the trailer causes the decoding scheme to ignore the subsequent code bits until the

Attention	Header	Main body	Trailer
Trigger Direction	ID Type Start	Actual info	Opposite dir. Inverse trigger

Table 3: Codeword structure

associated attention sequence is found. For bidirectional codes, a LIFO stack is used to store the codeword prior to decoding. Since codeword lengths vary for the different code types, a minimum number of default bits is required between codewords to avoid misinterpretation. The actual number of required default bits depends on the difference in length of the shortest and the longest codeword used.

The overall codeword structure is summarized in Table 3.

4 Encoding and Decoding

In this section, encoding and decoding of the above highway information is discussed. In order to automate encoding and to aid magnet installation, tables were generated from the highway survey data. Separate tables were generated for the two throughlanes and ramps. “Stations” denote a running counter (in meters) used by the survey to mark the distance traveled from the starting point. A sample table is shown in Table 4.

The code ID corresponds to the code identification incorporated into the header of a codeword. Magnet polarity ‘1’ is default and means “north pole up” for the magnet. In the left lane in the example in Table 4, codeword ‘45’ starts at station ‘13562.942’ with seven trigger bits (‘0100101’) and three directional bits (‘000’). Similarly, codeword ‘102’ starts at station ‘13567.742’ in the right lane. Note that the coding differs for the two lanes, mainly due to differences in merge/diverge and Highway lane/ramp ID coding.

Magnet type ‘1’ are default ceramic magnets, rare earth magnets on bridges are marked ‘0’, e.g. a bridge starting at station ‘13572.542’ for both lanes. Curvature is given in [1/m], with ‘0.0’ marking a straight section and ‘-’ denoting a left turn. In the example in Table 4, a left turning curve with radius $R_{curve} = 1/0.00131 \text{ m} = 763.36 \text{ m}$ starts at station ‘13564.142’. An additional table with merge, diverge and highway ID data was used to supplement the information in Table 4 with multi-lane data.

Left lane magnets			Stationing		Right lane magnets		
Code ID	Polarity	Type	Station	Curvature	Code ID	Polarity	Type
-	1	1	13560.542	0.0	-	1	1
-	1	1	13561.742	0.0	-	1	1
45	0	1	13562.942	0.0	-	1	1
45	1	1	13564.142	-0.00131	-	1	1
45	0	1	13565.342	-0.00131	-	1	1
45	0	1	13566.542	-0.00131	-	1	1
45	1	1	13567.742	-0.00131	102	0	1
45	0	1	13568.942	-0.00131	102	1	1
45	1	1	13570.142	-0.00131	102	0	1
45	0	1	13571.342	-0.00131	102	0	1
45	0	0	13572.542	-0.00131	102	1	0
45	0	0	13573.742	-0.00131	102	0	0
45	1	0	13574.942	-0.00131	102	1	0

Table 4: Example of a table for two lanes, containing highway survey and magnet polarity data

4.1 Encoding

Encoding was programmed using *Matlab*[©], based on the tables described above. First, the different code types are prioritized to minimize the number of different starting point indicators. For efficiency of encoding, only four different starting point indicators (see Section 3.3) are used, two short and two long distances from the end of an encoded codeword to the point where the contained feature information actually takes effect. Since codewords may not overlap and in fact require a number of magnets with default polarity between them, codewords may not always be placed at the desired starting location and priorities have to be assigned. For example, merge/diverge codes should always be placed sufficiently ahead of the actual merge/diverge location to allow preparation of the lateral control system, hence they were assigned the highest priority. On the other hand, permits for free lane change require long stretches of constant road geometry, without other coding, and hence should be encoded last.

Allocation of codewords first searches for a sufficiently large stretch with no prior coding, according to the preferred starting point indicator. If the designated codeword location is “occupied”, alternative starting locations are examined until an “empty” stretch is found. Bidirectional usage of the test track implies that most features have to be coded for travel in either direction, resulting in almost twice the number of codewords as would be required for unidirectional highways.

Once a suitable codeword location is found, the actual codeword is generated and encoded into the magnets. The 7-bit moving Hamming window of the attention sequence is similar for all codewords; however, the proper code reading direction has to be specified. Code header and main body are then broken up into 4-bit pieces, which are separately encoded using the 4/7-Hamming coding. The trailing sequence is again direction encoded to match the attention sequence in terms of reading direction and using the inverse of the 7 trigger bits.

The 4/7-Hamming code mapping of four information bits (i_4, i_3, i_2, i_1) into seven code bits $(c_7, c_6, c_5, c_4, c_3, c_2, c_1)$ first assigns the four i_k ($k = 1, 2, 3, 4$) to four c_l with $l \in [1 \ 7]$. The remaining three code bits $c_j \neq c_l$ are permutations of three-bit XOR combinations of the c_l and operate as correcting bits.

4.2 Decoding

Decoding is implemented in C as part of the QNX-based real-time lateral control system, using a finite state machine with states “search codeword trigger”, “read direction”, “read codeword forward”, “read codeword backward”, and “ignore n bits”. While in the state “search codeword trigger”, the last seven encountered magnet bits constitute the moving Hamming window and are decoded for detecting the codeword trigger of the attention/trailer

sequence, as described in Section 3.2. The event of finding a triggering code synchronizes the decoding scheme.

First, “read direction” of the next three bits determines the reading direction, forward or backward. Second, “read codeword forward” directly reads and decodes the header, and extracts code ID, code type, and starting point indicator. The inverse mapping of the 4/7-Hamming code is employed, yielding detection and correction of single bit errors within 7 code bits c_l . The three correction bits are XOR related to the three-bit XOR combination of information bits which was used to generate them. Read as a binary number between 0 and 7, the three correction bits point at the erroneous bit, if any. All three correction bits being zero means that no error was detected. After correction of a possible erroneous bit, the four information bits i_k ($k = 1, 2, 3, 4$) are extracted from the respective code bits c_l .

The code type determines the length of the main body, which is subsequently decoded. Next, the trailer is used to confirm proper reading of the codeword. Finally, the state “ignore n bits” re-initializes the moving Hamming window for trigger detection in “search codeword trigger”.

For “read codeword backward”, minor modifications have to be employed in step two above. Instead of direct decoding, read magnet bits are stored in a LIFO stack up to the maximal length of the longest codeword. Then, the LIFO stack is searched for the seven trigger bits of the attention sequence and decoding proceeds within the stack as described above for forward codes. However, the contents of uni-directional codewords are ignored; only bi-directional codewords like Highway lane/ramp IDs and Kilometer-posts are interpreted and transmitted to the vehicle control system. Furthermore, the final state “ignore n bits” is only employed if a code with maximum length was encountered. Otherwise, “search codeword trigger” is immediately called.

5 Results and Discussion

This paper discussed coding of road information in a lateral reference system using magnetic markers designed for Automated Highway Systems (AHS). The coding is utilized to communicate road information such as up-coming road geometry or lane merges/diverges from the roadway infrastructure to AHS vehicles. AHS subsystems “vehicle motion control”, “multiple vehicle coordination”, and “vehicle highway navigation” depend on various types of road information. The presented work is based on experiences with the preparation of the I-15 test track near San Diego, CA, for the National AHS Consortium demonstration in 1997. Information about road features was encoded into the magnets used as a lateral reference system for automatic steering control by exploiting binary polarity coding.

The I-15 test track near San Diego, CA, consists of two eight-miles long HOV lanes separated from the other lanes by concrete barriers, and a total of four ramps. Magnet installation

was supervised by CalTrans (California Dept. of Transportation) and concluded in Sept. 1996 with a detailed test, comparing the polarity coding tables with the installed magnets. Initial tests by PATH researchers in Nov. 1996 with a test car (Pontiac STE 6000) successfully decoded all codewords.

Despite the additional efforts related to bidirectional coding of the test track, sufficient room was found on the HOV lanes of I-15 to allocate all desired codewords. However, the on/off ramps proved too crowded to implement bidirectional coding. A possible solution is to stack several information codes into a single codeword. Code stacking decreases the overall required coding area by lumping several code headers and main bodies into one codeword with just one attention sequence and one trailer. The benefit of decreasing the number of attention and trailing sequences and of omitting “defaults” in between codewords is partly counteracted by the need of a high resolution for starting point indicators to accommodate varying distances from the codeword to the location where the coded feature actually starts. Alternatively, codes with multiple meanings were placed at either end of ramps on I-15, to be used together with small look-up tables for each ramp.

Though specifically designed for the I-15 test track, coding issues like feature selection and codeword structure, and encoding and decoding strategies were presented in a generic setting for ease of transferring the results to future AHS implementations. Specifically, the I-15 test track will be used for traveling in both directions, as compared to unidirectional travel on normal highways. Bidirectional coding required almost twice as many codewords as unidirectional coding, since most features had to be coded separately for each direction. Furthermore, the length of codewords is increased by the necessity to specify code reading directions and to use codeword trailers for bidirectional code reading. For future AHS implementations with unidirectional travel on the through lanes, less coding effort will result.

Coding road information proved to be an extremely reliable and readily implementable tool to create a communication channel from the roadway infrastructure to individual vehicles. Furthermore, coding of up-coming features like curvature transitions a short distance before the actual start of the feature is more reliable than using look-up tables, e.g. when entering an AHS roadway. High accuracy is achieved by relative distancing rather than absolute distancing from an AHS entrance. Nevertheless, the benefits of alternatives, e.g. using a Global Positioning System (GPS) in conjunction with extensive, detailed road maps remains to be examined.

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