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FINAL REPORT

Electronic Compass Option:
An Analysis of Calibration Techniques

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1 Executive Summary

1.1 Purpose

The original purpose of this study was to suggest ways in which the compass could be calibrated **before** the end of the assembly line. Such would allow a QC inspector to flag faulty units **before** they left the plant. However, since that problem has recently been solved, the emphasis of this report has now been shifted:

This report suggests ways of making the compass calibration procedure more efficient, while retaining accuracy in the compass operation. There are three key factors involved:

1. Cost/Convenience of Demagnetizing process
2. Cost/Convenience of Calibration process
3. Compass Accuracy

Each of these factors will be addressed for each suggested solution.

1.2 Conclusions

1.2.1 A combination of on-line (or off-line) demagnetization and off-line compass precalibration is expected to yield an accuracy which is sufficient for 8-point as well as a 16-point compasses.

1.2.2 The compass sensor can be moved to different locations and still retain its accuracy. This allows much variability in the demagnetization process, thereby allowing its cost/convenience to be optimized.

1.2.3 On-line demagnetization and calibration does not work. The accuracy is insufficient for even the 8-point compass to work well.

1.2.4 End-of-line calibration is acceptable for the 8-point and 16-point compasses, especially now that a QC check follows it.

1.3 Recommendations

1.3.1 **Short-Range** Implement off-line demagnetization with precalibration now. Demagnetization can be done at the compass calibration pad with a large demagnetizer that would eliminate variations due to operator error. Precalibration can be done by the compass supplier or by Ford any time before the compass is installed in the car.

1.3.2 **Mid-Range** Implement on-line demagnetization with precalibration. Automate the large demagnetizer used on the pad as recommended above. Place it on the line before the installation of the windshield, but after the roof is welded onto the body.

1.3.3 **Long-Range** Relocate the sensor on the center of the trunklid. Have the trunklid demagnetized, previous to its use in the assembly, with a stationary conveyor-belt based demagnetizer.

2 Introduction

Here we describe the major milestones of our investigation during the summer. The arrangement is in chronological order. For the definition of accuracy see section 3.11, page 5.

2.1 Present System Characterization

2.1.1 Accuracy of 96.4% is independent of the present demagnetization method. However, low level demagnetization is recommended to smooth out residual magnetism.

2.1.2 This level accuracy is also sufficient for the 16-point compass.

2.1.3 Vehicle alignment and calibration are very labor dependent.

Now came the time to try solutions. First we tried calibrating on the moving line.

2.2 Moving Line Calibration

2.2.1 Accuracy of 89.0% is independent of demagnetization. However, low level demagnetization is recommended to smooth out residual magnetism.

2.2.2 Accuracy of 89.0% is near the lower-bound tolerance for the 8-point compass and insufficient for 16-point resolution.

2.2.3 The calibration process must be modified for any structural changes in the relevant areas.

2.2.4 Small tolerance for physical calibrating area could result in large errors due to an operator-dependent process.

After this, we realilzed that our demagnetization procedure was inadequate. We then built a series of new, more powerful demagnetizers and tried the next approach:

2.3 Precalibration

2.3.1 Accuracy of 95.4% is dependent on demagnetization method.

2.3.2 A very consistent method of high level demagnetization must be implemented.

2.3.3 A labor-dependent Wixom calibration may be avoided.

2.3.4 This level accuracy is sufficient for the 16-point compass.

These results were very encouraging, but the cost of building a demagnetizer for actual use seemed high. This led to us considering alternative places for mounting the sensor which would ease the demagnetizing process or make it unneccessary.

2.4 Alternative Sensor Locations

2.4.1 General Comment

The accuracy is relatively independent of the transducer location.

2.4.2 Header

1. The module may be precalibrated in a standard car body.
2. Precalibration will require high level demagnetization between the spot welding process and windshield installation.

2.4.3 Rear-View Mirror Base

1. The module may be precalibrated in free space.
2. Degaussing may be eliminated or reduced to a low level.
3. The sensor must be remote from the module.

2.4.4 Deck-Lid

1. The calibration procedure may circumvent the manufacturing process.
2. The module may be precalibrated in a sub-assembly area of the plant.
3. High level degaussing may be done in a sub-assembly area of the plant.

We ran out of time before we could test these results on-line.

3 Glossary of Important Terms

3.1 Compass Module

The electronics associated with determining car direction using data from the flux-gate sensor.

3.2 Compass Sensor

The flux-gate coil. This is comprised of an iron core with three different windings on it. One carries the input voltage, and the other two carry the output voltages that give an indication of the direction of the car relative to the earth's magnetic field.

3.3 Magnetic Field

A magnetic field is a very abstract notion. The best way to think of it as a force field that acts on charged particles in a certain way. The overall effects of a magnetic field are familiar in the operation of a compass or of a magnet. The force has the ability to align slivers of iron to point in the direction of of the greatest force, the north pole in the case of a compass.

3.4 Magnetic Flux

This is similar to Electric Flux. Electric Flux is the familiar current flow of electric charge (electrons) in wires. Magnetic flux is the flow of magnetic current through materials such as iron, or even the air. This anology is very helpful in understanding the interaction of a magnetic field and a permeable material.

3.5 Permeable Materials

This is any material that allows flow of Magnetic Flux. This is very analogous to a "conductor" for Electric Flux. As with conductors, many materials are permeable (conductive), but only a few are permeable (conductive) enough to be called permeable materials (conductors). The most common permeable material is iron. It is a good "conductor" of Magnetic Flux.

Note that a "battery" in a magnetic circuit is windings of wire, and the "conductor" is the iron core of the transformer; as an example.

3.6 Transition Point

The present compass displays one of eight possible directions. If one drives the car in a circle, very slowly, the angular position where the display changes from one direction to the other is a **transition point**. Each one has a well-defined heading, i.e. where they should occur and where they really do occur. See the figure below:

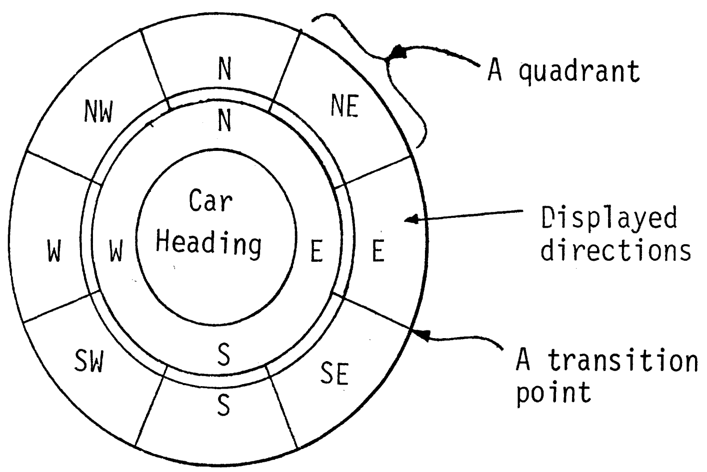

Figure 1: Transition Points and Quadrants for an 8-point Compass

3.7 **Quadrant**

This refers to the angular range of car headings within which the display does not change, when circling slowly as mentioned above. Notice in the figure above that there are eight quadrants, with the transition points separating them. A quadrant shift is defined as that situation where a transition point is measured at more than half a quadrant from its desired location. See the figure below:

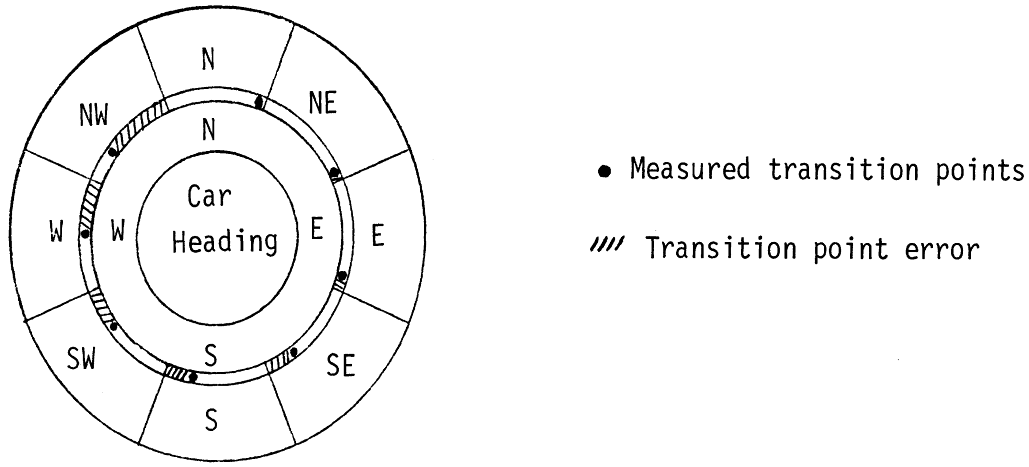

Figure 2: The Quadrant Shift

Here the shading indicates the error. Note that the N-NW transition point has gone through a quadrant shift, because the car will display N, when the car is clearly pointing NW. Such an error is too obvious for a customer to overlook or accept.

3.8 **Transition Point Error**

This is the cross-hatched areas shown in the figure above. Note, however, that this error can be signed if desired, or unsigned. We chose to use the unsigned error to get a true measure of the error, because how far off, not the direction of the error, is what is important in the accuracy analysis.

$$\text{Transition point error} = \mid \text{(measured transition point heading)} - \text{(theoretical transition point heading)} \mid$$

$$\text{Average transition point error} = \frac{1}{N}\sum_{i=1}^{N}(\text{transition point error})_i$$

where N is the number of samples taken, typically 32-64 for the 8-point compass.

Note that this error may be different depending on the direction of rotation of the car, the so-called "convergence error".

3.9 Convergence Error

This type of error may be described with the following illustration. As a car is rotated counter-clockwise from, say, the northeast to north, the compass converges on a point at which the reading changes from NE to N. As the same car is rotated clockwise from north to northeast, the compass transition point should converge on the same point. If the two points are not the same, then the angular spread between them is called the convergence error.

$$\text{Convergence Error} = |\,(\text{CW Transition point heading}) - (\text{CCW transition point heading})\,|$$

$$\text{Average Convergence error} = \frac{1}{N}\sum_{i=1}^{N}(\text{Convergence error})_i$$

where N is the number of samples taken, typically 32–64 for the 8-point compass.

The convergence error is assumed to be independent of the transition point error.

3.10 Standard Deviation

This is a general measure of the variability in a set of data:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left((\text{transition point error})_i - \text{average transition point error}\right)^2}$$

3.11 Compass Accuracy

A measure of the ideality of the total performance of the compass. This is based on the idea that 0.0 % accuracy is the case for a compass if it tells you the exact opposite direction to that which you are actually going. Thus:

$$\text{Accuracy} = 100\% \times \left(1 - \frac{\text{Average transition point error}}{180^\circ}\right)$$

Note that the best case is when the average error is zero, which gives Accuracy=100% . We can specify the minimum allowable accuracy be specifying a maximum allowable error for the compass.

For an 8-point compass $(\text{avg error})_{max} = 22.5^\circ$ which gives Minimum allowable accuracy $= 87.5\%$.

For a 16-point compass $(\text{avg error})_{max} = 11.25^\circ$ which gives Minimum allowable accuracy $= 93.5\%$.

These are the guiding parameter values in our measurements and assessments.

4 Physics of Magnetic Fields

4.1 Interaction with steel/iron

There are two major interactions between magnetic flux density fields and metallic vehicles. The first is the perturbation of the earth's flux lines by the car body. The second is the induced residual magnetism in the permeable metal of the component parts.

Current flows in the path of least resistance. Similarly, magnetic flux flows in the path of least reluctance. Free space has a high reluctance compared with a permeable metallic body. Hence, a predominantly iron vehicle will tend to concentrate flux lines. This produces a higher flux density where perturbations produce component vectors in the same direction and a lower flux density where component vectors combine destructively. Lines of magnetic flux enter iron/steel bodies at normal incidence. Therefore, the field will change direction very rapidly across sharp structural discontinuities.

Residual magnetism in a permeable structure produces an external magnetic field in the same way as a permanent magnet. This effect is due to the spin and the orbital motion of the electrons around the nucleus of an individual atom. The orbital motion of the electrons around the nucleus produces a magnetic field that opposes any change to the existing magnetic field of the atom. This effect is called paramagnetism. For predominantly iron structures this effect is negligible and may be ignored. As the electrons orbit around the nucleus they also spin about their axis much the same way as the earth spins about its axis as it orbits around the sun. Each spinning electron represents a magnetic dipole, which is the smallest element of a permanent magnet. Similar to the earth, each magnetic dipole has a north and south pole. Individually, each dipole produces a very small magnetic field, however, when dipoles of adjacent atoms have the same spin axis, the total field increases significantly. This effect is called ferromagnetism. In metals like iron, there is spontaneous alignment of individual electron spins in small volumes called domains. The domains are small but macroscopic with volumes ranging from 10^{-9} to 10^{-18} cubic meters. Since there are 8.5×10^{28} atoms of iron per cubic meter, on the average, a domain contains about 10^{16} atoms. A polycrystalline material such as iron has many domains in each grain, however, the domains are randomly oriented with respect to each other and therefore the entire structure produces no external magnetic field. Variation in the magnetic state of permeable metal is due to a number of factors which include : variation in material composition, heating and cooling, welding, and stress due to molding and stamping. Given the current manufacturing process, it is virtually impossible to insure that any two cars have the same magnetic state. Test data taken with a magnetometer shows residual magnetism of over 2 Gauss with erratic changes in polarity for most parts of any Mark VII or Lincoln Continental. Since the compass transducer senses a field on the order of 0.5 gauss, residual magnetism is a critical concern in the analysis of the compass operation.

The perturbation of the flux lines by the car body is taken into consideration by the calibration process. The calibration also compensates for residual magnetism, however, the feedback system used in the compass module may not be strong enough to null out high field residuals. Therefore, some type of degaussing is necessary to keep the residual magnetism to a minimum.

4.2 Demagnetization

The most effective method of demagnetizing permeable objects is the application of a modulated time-varying magnetic field. This approach uses the hysteresis property of ferromagnetic materials to produce a random orientation of domains with respect to each other and thus, no net external field. The two most common methods of achieving this are with air-core and iron-core coils.

The air-core coil produces a relatively uniform field across it's mid-section, see figure 2. The open loop design is most suited for demagnetizing objects which may be passed through the center while either the loop or the object changes its orientation. It is important to note that demagnetization only occurs when the amplitude is gradually decreasing. The modulation may be achieved in two ways. The first way is to use a variable voltage source such as a variac. Using a variac allows the coil to be placed on the surface to be degaussed prior to operation. The sinusoidally varying voltage is gradually increased to a maximum and then gradually decreased to zero. The second way is to start with the coil physically removed from the surface, but with it running at maximum strength, and move it gradually closer to the object and then gradually away. Both of these applications cyclically reduce the hysteresis curve down to virtual zero. However, each method has a different effeciency in a practical sense. When the coil is held in free space, it represents a very high reluctance magnetic circuit. This means that the inductance in the coil will be at a minimum and the current will be at a maximum. There will be a significant amount of power dissipated as joule heating from

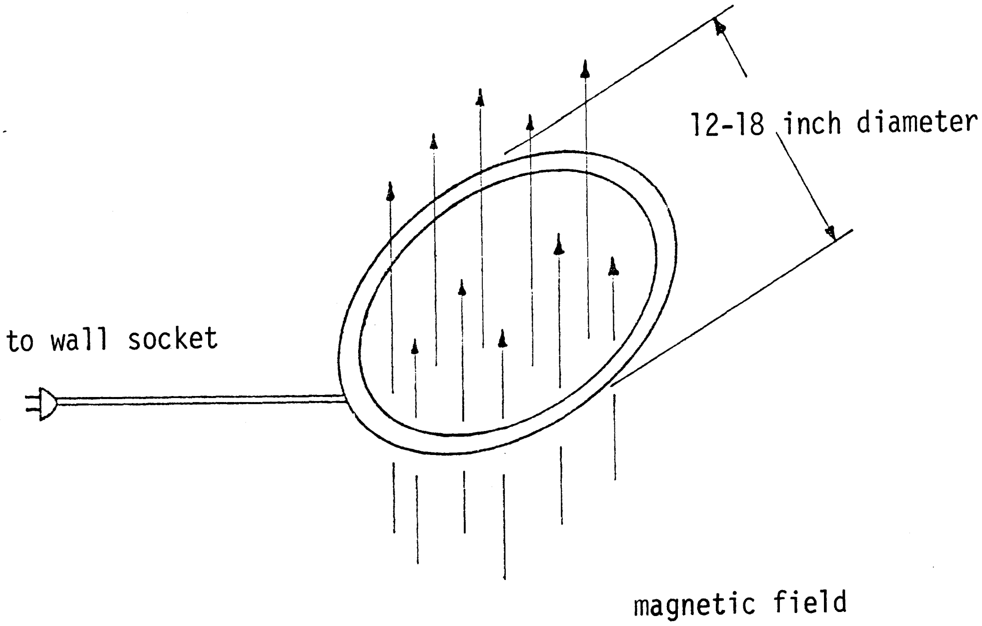

Figure 3: Air-Core Coil

the coil. When the coil is placed on a permeable surface, such as a car top, the reluctance of the magnetic circuit decreases dramatically. This causes an increase in inductance of the coil which decreses the current. The result is a decrease in the joule heating of the coil. In return, the magnetic energy density is increased and there is power dissipated into the metal surface of the car in the form of joule heating. Therefore, the most effecient system would have the coil as close to the surface as possible prior to excitation. The sinusoidal input is slowly increased and then decreased to zero. Using this procedure is advantageous if the coil is to be used for nearly continous duty. For example, demagnetizing sub-assembly parts would require a high duty cycle. The air-core coil currently used at the Wixom plant has a center field strength of about 60 Gauss. A field strength of this magnitude was sufficient to smooth out transient residuals caused by spot welding across the front of the header. However, these residuals seemed to have very localized domains on the surface of the metal. Thus, the coercive force needed to randomize the domains was supplied by the 60 Gauss coil. Residuals created during the sheet metal formation appear to be much more difficult to remove. Magnetometer readings show that the 60 Gauss coil will reduce a 2 Gauss residual down to about 1.8 Gauss. However, the coil is ineffective beyond this point. This is certainly due to the small amplitude of the coil and possibly compounded by the fact that the field is basically perpendicular to the surface of the car. Horizontal electron spins would not be affected by a changing vertical field.

The iron-core coil is inherently a much more powerful source of a magnetic field. For our purposes we will examine the horse-shoe type of electro-magnet. See figures four and five. The horse-shoe degausser provides a low reluctance flux path which creates very strong perpendicular and transverse field components. This insures that all domains will be exposed to a parallel magnetic field. As figure four suggests, two coils, one around each leg are connected in series and driven by a sinusoidal source. Figure five shows the core which is composed of insulated laminations similiar to those used in transformers. Due to the weight of the iron core, this type of degausser should most likely be counter-balanced. As the magnetic polarity of the demagnetizer changes, the target surface is magnetized, demagnetized and remagnetized with changing polarity. For a 60 Hz power source, this is done 60 times per second. For each cycle there are two times when the polarity is reversed. Since magnetization occurs almost instantaneously for ferromagnetic materials, there will always be a net pulling force exerted on the surface. However, there will be vibrations due to the repulsive force at the instant when the demagnetizer and the surface are at opposite magnetic polarities. Due to the weight and the strong attractive force, the demagnetizer should always be in contact with the surface, while in operation, to avoid injuring the target surface. Fortunately, the transverse force is minimal so the demagnetizer may be moved horizontally over the surface with relative ease. The geometrical shape of this degausser allows the horseshoe to surround the edge of a surface to more effectively remove transient residuals. A device similar

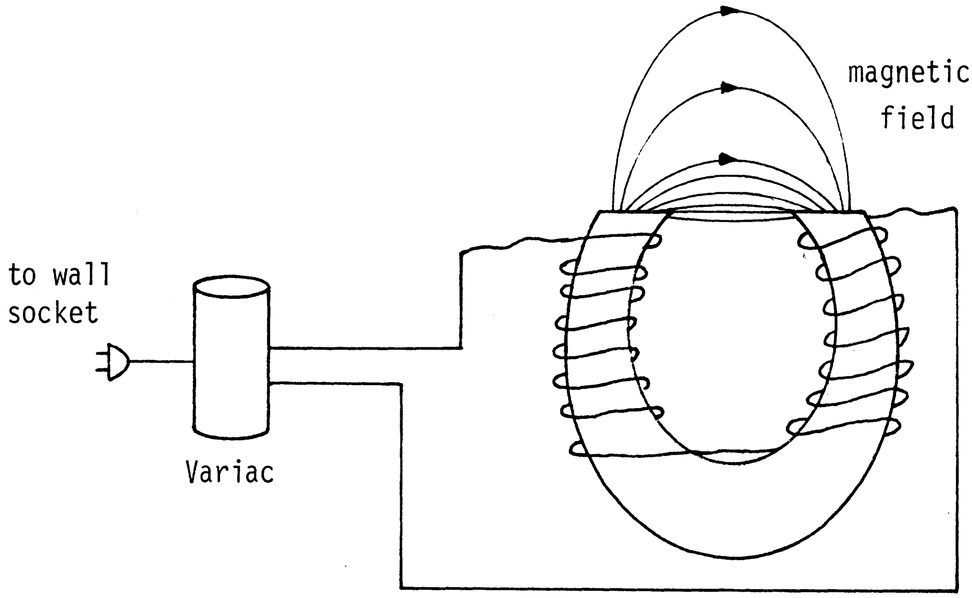

Figure 4: Horse-Shoe Demagnetizer

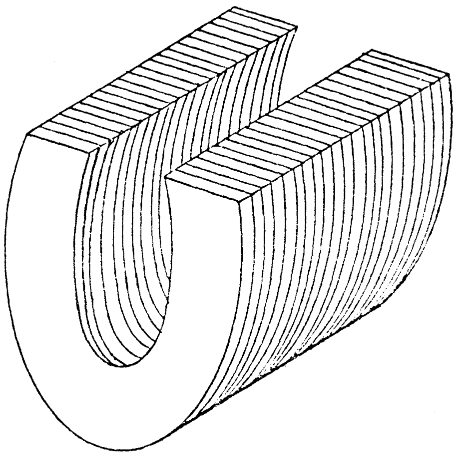

Figure 5: Iron Core Showing Laminations

to the horse-shoe demagnetizer that we built was tested at the Wixom facility. The field strength of the test model was approximately 450 Gauss. Magnetometer readings show residuals of over 2 Gauss reduced to less than 1 Gauss. However, this field strength was still not suffcient to produce magnetic homogeneity among vehicles. It would appear that a stronger field is required.

In summary, if magnetic uniformity is not critical, then the air-core coil is sufficient to allow proper calibration. Currently, this would apply to off line and moving line calibration. However, if all vehicles must be reduced to the same magnetic state, then a iron-core type of demagnetizer is more appropriate. This is certainly a requirement for any type of precalibration. It should be noted that application of both types of demagnetizers is very operator dependent. Any type of discontinuity caused by either physical movement or a transient in the power source may establish transient residuals.

5 Discussion of Results

5.1 Summary

Many months were spent testing cars as they came off the assembly line in Wixom. First the accuracy of the present calibration method was determined. Next, a method of on-line calibration was tried, but quickly showed to be unacceptable. Now, demagnetization methods were recognized as being critically important to the final goal of compass precalibration. Different methods were tried with varying success, but the idea was shown to be a viable solution. Lastly, the compass sensor was moved to different locations in the car and its accuracy measured, in an effort to determine positions that could be demagnetized more easily and uniformly, if necessary.

5.2 Present System Accuracy

Each compass is currently being calibrated at the end of the manufacturing process in an off-line location. This location, called the calibration pad, consists of two vehicle alignment guides. The first guide is parallel to magnetic north and the second guide is perpendicular to the first. Calibration requires a two-step process. The car is initially aligned with magnetic north so that the longitudinal coil should sense no flux. Any detected field is nulled out and the current required is related to the angular deviation of the field. A similiar procedure is used for the latitudinal coil when the vehicle is rotated 90 degrees to point toward the west.

A sample of 20 vehicles, 10 of each model, were calibrated off-line and tested in a vacant lot outside the Wixom plant. There we slowly drove the car in circles to determine the accuracy of its compass. Two sets of data were taken. The first set of tests were done on cars which had been degaussed with the air-core coil. A second set of tests was completed on vehicles that had not been degaussed. A surveyor's transit was used to measure the angular position of the vehicle relative to magnetic north. The transit was aligned such that the hood emblem and the rear-view mirror stem were parallel to the transit scope. The precision of the transit compass was to the nearest half degree. The following table summarizes the results of the analysis. The complete test data is listed on page 18.

Table 1: Accuracy of Present Calibration System

Demagnetizing?	yes	no
Average Transition Point Error	6.6°	6.4°
Standard Deviation	10.0°	10.0°
Average Convergence Error	5.0°	4.0°
Standard Deviation	3.0°	3.5°
Accuracy	96.3%	96.4%

The data in table 1 indicate that on the average, the transition point occurs at plus or minus 6.6-6.4 degrees from the theoretical value. This implies an uncertainty region of about 13 degrees centered on the correct value. Demagnetization appears to have only a small impact on the accuracy. In fact, here the data show that demagnetizing reduced the accuracy. The standard deviations give a measure of the variability of the sample data.

It should be noted, however, that **never** was a transition point measured to be outside it's quadrant.

This preliminary data gives an idea of the average performance of a working compass. With this knowledge, new configurations of both compass and calibration can be judged as sucesses or failures. The following sections describe some new calibration procedures and these are judged in the same way.

5.3 Precalibration Feasible

The most promising of the methods tried was a thorough demagnetization of the region of the car surrounding the compass. In the best case this allowed a compass calibrated in one car to work as accurately in another car. This is very suggestive of the idea that precalibration of all the compasses is possible.

Precalibration offers the opportunity to eliminate the need for a Wixom calibration. There are two major ways to precalibrate the electronic compass. The first way is to incorporate offsets into the software. This would require experimentally determined calibration constants. The second way is to calibrate each module in a standard car body. Variation between individual modules would still be taken into account by the latter method. Both schemes require the vehicles to be magnetically homogeneous. Therefore, a very strong demagnetizer is necessary. Also, a consistent demagnetizing application procedure must be followed.

Presently, the calibration procedure must be done on each car separately, due to the car-to-car variability of the spacial distribution of magnetic domains. The demagnetization procedure that was used eliminated this variability from car-to-car and so allowed precalibration to work.

The precalibration tests were performed by simulating the second method of precalibration. This involved interchanging calibrated modules among magnetically uniform vehicles. The roof area above the header was extensively degaussed using an iron-core coil with a field strength of approximately 450 Gauss. Magnetometer readings showed a residual magnetism variation of about 0.3 Gauss between cars.

The method used involved demagnetizing two cars of the same model; calibrating the compasses; switching the compasses; and then measuring their accuracy as before. The results are shown below.The complete test data may be found on page 23.

Table 2: Precalibration Feasible

Average Transition Point Error	8.3°
Standard Deviation	9.3°
Average Convergence Error	4.5°
Standard Deviation	4.2°
Accuracy	95.4%

Quadrant shifts never ocurred during these measurements. These results are consistent with the average performance of a working compass as set forth in table one. However, this is at the expense of a much more rigorous degaussing procedure. The conclusion is that precalibration with demagnetization will work sufficiently well for both 8-point and 16-point designs. However, some care must be taken in demagnetizing correctly. See section 11.2 in the appendix.

5.4 Relocation of Sensor Possible

Another area of interest in this study was the investigation of different places for the compass sensor. There are a few reasons for wanting to do this:

1. Be able to relocate compass display without worry of compass sensor performance being degraded or a demagnetization scheme being significantly altered.
2. Be able to demagnetize the part off-line so that precalibration still works.
3. Possibly eliminate the need for demagnetizaion by choosing an area such that the compass can be precalibrated without a demagnetization step.

The method involved using a Mark VII test car. The compass was moved to various places in the car, calibrated, and then tested. No demagnetization was performed as this is only useful for testing precalibration accuracy by switching compasses between cars.

5.4.1 Header

The header is the current location of the compass sensor. The most critical factor to be considered for this location is the transient residuals caused by spot welding across the front roof area. This area requires demagnetizing independent of the method of calibration. If precalibration is required the demagnetizing should be done after the spot welding but before the windshield is installed. This allows the horseshoe type demagnetizer to enclose the front edge of the roof and more effectively "remove" the residual magnetism.

5.4.2 Rear-View Mirror Base

The rear-view mirror base offers an excellent possibility from the standpoint that demagnetizing may be minimized or even avoided. Preliminary tests were performed using a remote core which was attached to the mirror base. There was no demagnetizing. The compass was calibrated with the sensor attached to the mirror base. Magnetometer readings showed residual magnetism of 1.0-1.3 across the front roof. The data is summarized below. Complete data on page 28.

Table 3: Mirror Base Results

Average Transition Point Error	9.5°
Standard Deviation	6.1°
Average Convergence Error	8.0°
Standard Deviation	4.3°
Accuracy	94.7%

Precalibration may be tested by calibrating a compass in free space and then installing the module in the car with the core attached to the mirror base. This will test the possibility of precalibration in freespace as opposed to precalibration in a model car body. Note , however, that the solenoids in the automatic mirror-flipper may compromise this performance during actual use.

5.4.3 Deck-Lid

The deck-lid provides a convenient location for the compass sensor which may be installed in a subassembly area of the plant. This alternative would allow degaussing and installation to occur before the regular process has begun on the vehicle. The table below summarizes data taken with the compass sensor located in the center of the deck-lid, and the compass calibrated in that position. The complete data may be found on page 28.

Table 4: Center Deck-lid Results

Average Transition Point Error	6.2°
Standard Deviation	2.0°
Average Convergence Error	5.4°
Standard Deviation	3.4°
Accuracy	96.6%

A sensor placed on the trunklid appears to allow precalibration to work if just the trunklid is demagnetized, which can be done off-line. This has not been experimentally verified.

Note that all these were one-run measurements. We only had one car and one compass,and limited time. All of the places we tried worked fine except the one in the trunklid that was completely enclosed by steel. Therefore, any mounting bracket for the sensor at these new locations must not be made of steel.

Two locations that we tried and appear to be far enough away from large steel sheets that car-to-car variability may not be noticed by the sensor are the gas tank inlet and the rear-view mirror base. This may allow precalibration without demagnetization. One problem with the mirror base is the solenoids in the mirror. It is unknown whether they would interfere significantly with the compass readings. Neither of these ideas have been experimentally tested.

5.5 Proposed On-line Calibration Unacceptable

A proposed solution to the present off-line calibration problems was to calibrate on-line. Two sites, one on a line pointing North, the other West, were needed. These sites were chosen so that nearby steel structures were kept to a minimum. This was necessary to have minimal interference with the Earth's magnetic field. The differences between this on-line scheme and the present off-line method are:

1. On-line demagnetization and calibration are done while the car is moving.
2. The on-line North and West calibrations are done at very different places and times.
3. The variability in the calibration times from car-to-car means that each car travels a different distance while calibrating. Therefore, this exposes each car to a different, and time-varying, external magnetic field.

The most critical concern for a two-step moving-line calibration is to find a line heading magnetic north and a line heading perpendicular 90 degrees to the west. The Wixom facility has a true north line and a true west line. The declination, which is the angle between true north and magnetic north, for this geographic location is approximately 4 degrees, see figure below.

However, the field along the north and west lines has a measured declination which varies between 3 and 7 degrees. The most feasible location for the north calibration is the last 20-50 foot area just prior to the dynamometer station. The west line calibration may be completed anywhere on the first west line following the dynamometer area. The testing procedure used for the moving line calibration was basically the same as for off-line calibration except that every car was demagnetized with the air-core coil. There was a logistical problem due to the fact that the hood could not be closed completely.

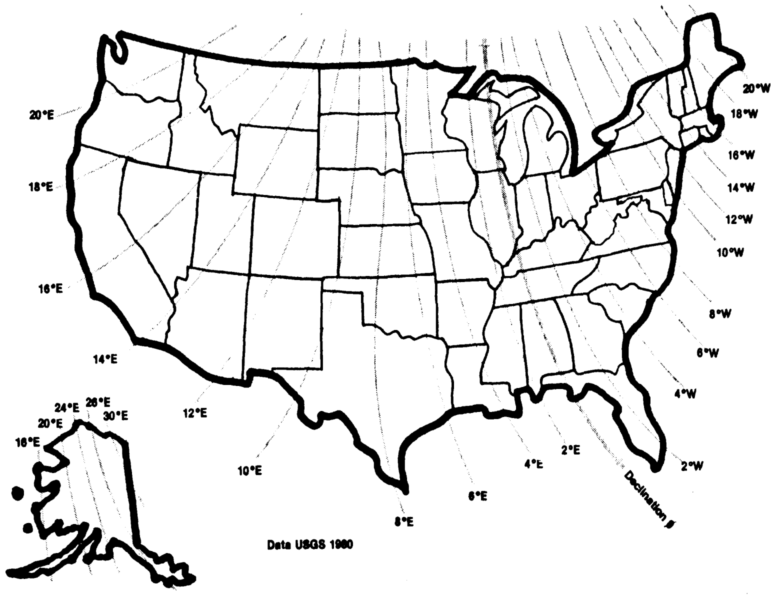

Figure 6: Declination Chart for the United States: USGS 1980

The following table summarizes the results of the moving-line analysis. The complete test data is listed on page 30.

Table 5: Unacceptable On-line Calibration Results

Average Transition Point Error	20.0°
Standard Deviation	23.0°
Average Convergence Error	7.3°
Standard Deviation	5.0°
Accuracy	89.0%

As the data suggests, there were many instances of quadrant shifts for each car. This is completely unacceptable. Every car had at least one quadrant shift.

The data in table 5 indicates that, on the average, the transition point occurs at plus or minus 20 degrees from the theoretical value. This implies an uncertainty region of about 40 degrees centered on the correct value. The convergence error is relatively consistent with the same error as for the off-line analysis. This reinforces the assumption that transition point error and convergence error are independent. The accuracy is significantly lower than that for off-line calibration.

The data in the Appendix also shows a ten-second variability in the length of calibrations, as alluded to earlier. Note that despite this ten seconds being significant in this case, it is far less that the variability observed during off-line calibration, which was on the order of thirty seconds. We cannot explain this difference.

This shows that, practically, the on-line scheme does not work. However, very little insight into why it doesn't work has been gained. Further experiments may be able to show that some on-line calibration scheme may work.

6 Summary of Conclusions

6.1 Demagnetization makes the cars sufficiently equal that the compass can be calibrated in any demagnetized car and then will work with sufficient accuracy in any other car of the same model. This is true for both 8-point and 16-point compasses.

6.2 Our demagnetizers were too weak to demagnetize the cars completely. Instead we set up a nearly uniform magnetic state in the area surrounding the sensor. It was this uniformity that allowed the compasses to be switched and still work. Ideally, a more powerful demagnetizer should be used that can bring the magnetization of the steel to a lower level. See section 4.2 for further details.

6.3 Note that demagnetization does **not** eliminate the effects of the steel in the car on the field measured by the compass. The compass calibration procedure does this. Demagnetization merely (1)eliminates the **variation** of the magnetization in the steeel due to manufacturing and (2)lowers the **magnitude** of the magnetization to a level comparable with that of the earth. This ensures:

a. Magnetic equality of cars of a certain model, with respect to the compass sensor.
b. Precalibration of both 8-point and 16-point compasses will work.
c. No decay of high fields, over time, that would cause a working compass to lose calibration.

6.4 The on-line calibration scheme does not work. It is not known **why** this doesn't work. Some possibilities are:

a. The uneven and time-varying fields that the car is subjected to while in the moving line.
b. Other moving equiptment
c. Inability of compass calibration to compensate for the extreme effects of shielding due to the geometry and amount of steel in the area.

It must be noted that demagnetization appears to have no effect on the accuracy here.

6.5 The relocation of the compass sensor is feasible. Suggested places are:

a. Trunklid
b. Mirror Base
c. Fuel Tank inlet shroud

All mounting brackets must be made of non-magnetic materials– no steel.

6.6 The effect of demagnetization before calibration in the present system is small. It merely allows less calibration current to be used, and therefore makes the calibration process some tens of seconds shorter. The compasses are not more accurate if demagnetized in this way.

6.7 The demagnetizer presently used does not effect the magnetization state of the roof of the car appreciably. Therefore, decay in the magnitude of the magnetic state over time may effect the accuracy of the compasses. This does not appear to occur in such magnitude that the compass function is compromised, though. However, in later designs, where more accuracy is required, this may be noticeable.

7 Future Study

7.1 Loose-ends of the Present Project

Many loose ends need to be tied up in the future. These include:

1. Strength, size and geometry of demagnetizer needed in each specific case of compass sensor placement.
2. Investigate decay, over time, of the induced magnetization in the steel.
3. Analysis of precalibration procedures for differently-located compass sensors. (ie. will precalibration work in these new locations?)
4. Method(s) of precalibration.
5. Possibility of model-independent precalibration/compass-location combination.
6. Possibility of a sensor location that does not need demagnetization in order for precalibration to work.

7.2 16-Point Compass

If the average transition point error remains comparable to the 8-point level, then the 16-point compass will appear to be more accurate. The theoretical upper limit for transition point error is 11.25 degrees for a 16-point compass. If the error is greater than 11.25 degrees, then on the average, the compass will shift over $\frac{1}{4}$ of a quadrant.

7.3 Self-Contained Navigation System

The self-contained navigation system outputs the vehicle location relative to an arbitrary reference point. There are basically two variations of this type of system. The first system is strict navigation with an optional destination input. The second system is a short range vehicle monitoring system.

The basic system requires three inputs with an optional fourth input. The first input is the starting position of the car. This is the odometer reading and may be manually entered or automatically entered when the ignition is turned on. The second input is the incremental distance traveled, which is also sampled from the odometer. The third input is the direction, which is derived from the compass. The optional fourth input is the destination. The driver would enter the compass direction and the distance along the route. The inputs are processed by the system to arrive at the current position relative to the reference point.

A vehicle monitoring system would send the same output information viewed by the driver back to the reference location. For example, when the family car is used, the output information is continuously transmitted to a receiver in the home where it is stored. This will allow other family members to locate the vehicle. This type of system has been tested for use by police cars and taxicabs.

APPENDIX

A 1 Demagnetization Methods

A 1.1 Air-Core Coil

This is a coil of wire, 12–18 inches in diameter, with many turns of wire. This plugged directly into the wall outlet. The field produced by such a coil is perpendicular to the plane of the coil, varies sinusoidally with the line voltage. See the figure below:

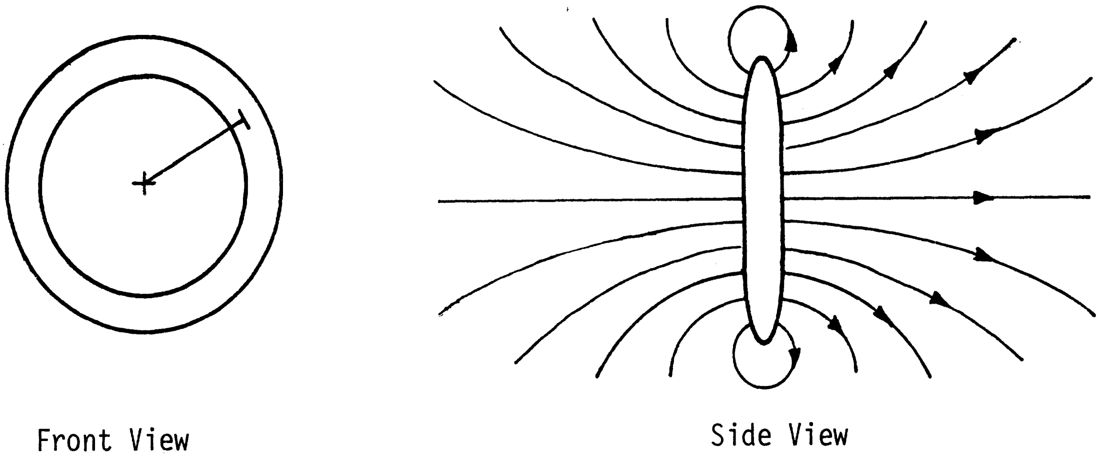

Figure A 1: Air-Core Demagnetizing Coil

The coil is used by holding it on the surface of the roof of the car, near the compass, and slowly moving it around. This action demagnetizes the magnetic domains of the metal. The maximum strength of our coil was 60 Gauss, and so domains stronger than this were unaffected by the coil. The coil was used in the studies reported in sections 5.1 and 5.4.

A 1.2 Annis Corp. Demagnetizer

This was a small device that fit in the palm of a clenched hand. It consisted of a curvy-shaped core of iron, with many turns of wire around it. It too plugged into the wall socket. See the figure below. The flat base was used to demagnetise the roof, while the probe-like end was used to demagnetize the brackets and screws within the roof cavity, near the compass. Using a magnetic field sensor, the demagnetization process was continued until the most uniform magnetic state possible was produced.

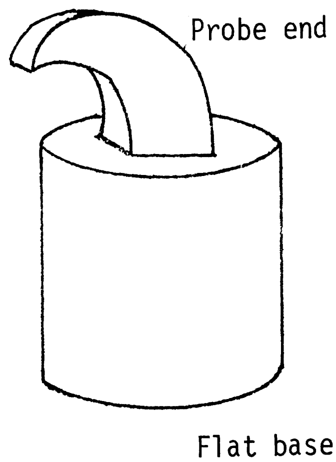

Figure A 2: Annis Corp. Iron-Core Demagnetiser

This demagnetiser was used in the studies discussed in sections 5.2, with the Continentals, and A4.2, on precalibration. The maximum strength of this unit was 250 Gauss.

A 1.3 **Lab-Built Demagnetizer**

By this time we had decided that we needed a larger and more powerful demagnetizer. We built our own using an old transformer. It was 2-3 times larger in size than the Annis model. See the figure below. In demagnetizing, this unit was uniformly pushed across the surface of the entire front half of the roof, with the Annis unit still being used inside on the brackets and screws. This demagnetization scheme worked the best.

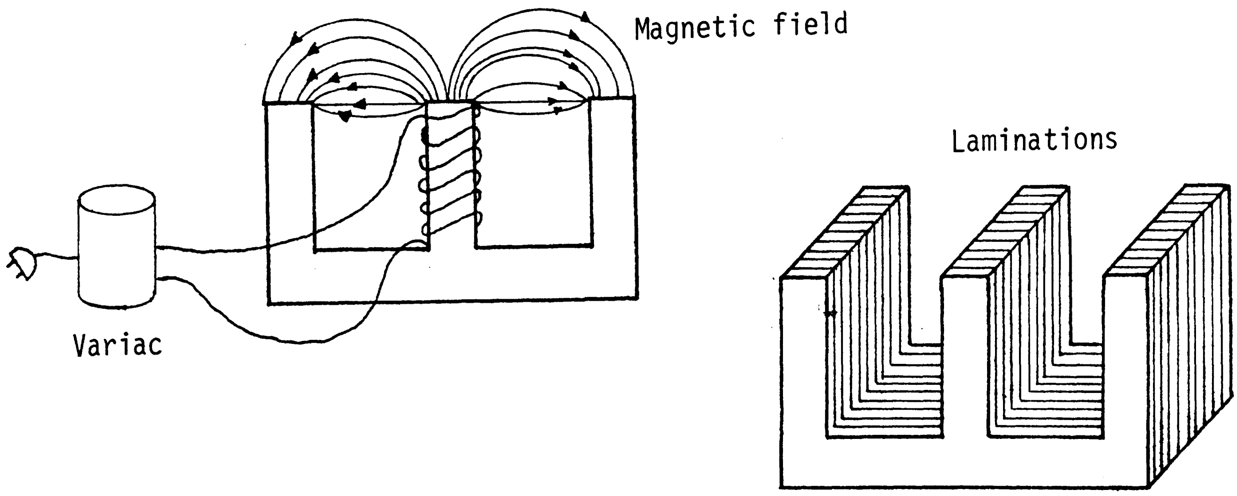

Figure A 3: Lab-Built Iron-Core Demagnetizer

Note that we used a variac with the unit, giving us 140 Volts maximum rather than just 110 Volts from the wall. The maximum strength of this unit was 230 Gauss. This unit was used in the study reported in section 5.2 on the Mark VII's.

A 1.4 **Other Demagnetization Methods**

Industrial demagnetization of small parts is done by passing the parts through a large, stationary demagnetizing coil with a conveyor belt. A similar system could be used for the demagnetization of the deck-lid, if desired. However, it is unlikely that anything as big as an entire car could be demagnetized this way, due to high cost of such an apparatus, as well as the 20-30 feet of space needed on the assembly line.

A 2 Calibration Methods

This section basically concerns the calibration sites, the methods of pushing buttons on the compass is the same in all cases.

A 2.1 Off-Line

Within the plant, at the end of the line, is a section with two metal rails bolted to the cement. One points North, the other West. Car tires fit the grooves. First, the car is calibrated North, then West, then driven out into the lot. There are some large steel obstructions nearby, although this appears not to matter. The car is stationary while calibrating. The two rails are within ten feet of each other. This is the present system. It was used for the data reported in sections 5.1 and 5.2 .

A 2.2 Precalibration

The normal off-line calibration method was used. However, the compasses were switched to different cars after the calibration was finished. This simulated an actual precalibration. This method was used for the data reported in section 5.2.

A 2.3 Parking-Lot Calibration

This involves lining the car up with a surveyor's transit, both North and West, while out in a deserted parking lot. This was done for the data in section 5.3 and worked at least as well as calibration on the pad.

A 2.4 On-line Calibration

For North, the site was just before headlight alignment. There was a large ventilation structure nearby; and, of course, other cars. The car moved while being calibrated. For West, a point on the next line was chosen that was far from any steel structures. The two sites were separated by about 500 feet and often an additional time for repair after going through dyno testing. Possibly one or all of the three factors below combined to keep the calibration from being successful:

1. Difference of nearby steel obstructions.
2. Difference in position in factory. (i.e. difference in distant steel structures)
3. Time lag between the two calibrations.

This was used for data reported in section 5.4 .

A 2.5 Other Calilbration Methods

Using a car body buck, the compasses can be precalibrated before they are put into the car. This would correct for compass-to-compass variation, while demagnetization of the car would remove the variability.

It's also possible that the compass software program could be modified so that calibration is unnecessary, however, then the compass variability would not be accounted for. It is not known whether the compass variability is large enough to be an important factor.

A 3 Data Acquisition Method

As mentioned in section 5, this involved slowly driving the car in circles and recording the heading of the car at a transition point. (see section 3 for the definition of a transition point) A surveyor's transit was used to measure the heading of the car. A transit is merely a precisely calibrated and well-marked compass. It can be leveled with respect to the earth. It also has a short-range viewer with cross-hairs that that can be used to sight an object. The heading of the car is then computed using the heading of the viewer. In our case, the viewer was lined up with the middle of the hood, or the hood ornament, and the mirror base on the windshield. The measurements had an accuracy of 0.5° due to the accurate transit measuring system. Before measurements, the car was driven in a slow figure eight to "confuse" the compass into an unbiased state.

A 4 Data Tables

A 4.1 Present System Accuracy

1. Ten cars each, Mark VII and Lincoln Continental, were calibrated without demagnetization at the present site in the plant and tested outside for Transition point error analysis.
2. After each car in part one was tested, it was brought back to the calibration site where it was demagnetized with the air-core coil for 25 seconds, recalibrated, and taken outside for re-testing.

The following pages present the raw data tables as well as some averaging of the data, with appropriate statistical error measures. Below is a key to the symbols used in the tables.

Key to Symbols	Key to Responses
D – Demagnetization	Yes or No
R – Rotation of Car	CCW – Counter-Clockwise CW – Clockwise
CM – Car Model	LC – Lincoln Continental MS – Mark VII
IN – Null Current Required in North Calibration	One unit is 56.8 μ A
IW – Null Current Required in West Calibration	One unit is 56.8 μ A
NNE – Transition Point Heading	To the nearest Half Degree
ENE – Transition Point Heading	To the nearest Half Degree
ESE – Transition Point Heading	To the nearest Half Degree
SSE – Transition Point Heading	To the nearest Half Degree
SSW – Transition Point Heading	To the nearest Half Degree
WSW – Transition Point Heading	To the nearest Half Degree
WNW – Transition Point Heading	To the nearest Half Degree
NNW – Transition Point Heading	To the nearest Half Degree
CTN – Calibration time for North	To the Nearest 0.1 sec.
CTW – Calibration time for West	To the Nearest 0.1 sec.

D	R	CM	IN	IW	Transition Points								CTN	CTW
					NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW		
					22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5		
No	CCW	LC	-8	-32	20.5	58.0	113.0	162.0	205.5	264.0	301.0	338.5	7.1	28.9
	CW				21.5	63.5	102.5	162.5	207.0	252.0	305.0	341.0		
Yes	CCW	LC	-3	16	21.5	70.5	123.5	164.5	205.0	243.5	295.0	334.0	3.9	15.7
	CW				22.5	70.5	121.5	164.5	206.0	242.5	287.0	337.0		
No	CCW	LC	-27	21	18.5	67.0	113.5	158.5	197.5	247.0	292.5	336.5	22.5	17.8
	CW				30.0	66.0	113.5	168.5	204.0	234.0	293.0	342.0		
Yes	CCW	LC	-81	-17	32.0	66.0	102.0	143.0	188.0	246.5	306.0	355.5	64.0	16.0
	CW				20.5	67.0	104.0	144.0	188.0	246.0	307.0	353.0		
No	CCW	LC	1	-58	18.0	73.5	125.0	165.0	205.5	244.5	294.0	334.5	2.6	53.1
	CW				26.0	71.5	128.0	163.0	211.0	246.5	291.0	329.0		
Yes	CCW	LC	0	9	35.0	77.5	120.5	155.0	194.5	239.5	290.0	339.0	1.5	10.9
	CW				30.5	74.5	119.0	160.5	201.0	241.0	292.5	342.0		
No	CCW	LC	-45	-18	24.5	69.0	120.0	154.5	192.5	237.5	302.5	342.0	39.5	17.5
	CW				26.0	67.5	120.5	156.5	190.5	237.5	302.0	350.0		
Yes	CCW	LC	-6	-7	18.5	68.5	125.0	167.0	201.0	237.5	297.5	346.0	6.3	10.4
	CW				17.0	65.0	125.0	165.0	199.0	237.5	293.5	341.0		
NO	CCW	LC	-7	-49	28.5	67.5	112.5	155.0	200.5	250.0	304.5	346.0	6.8	38.9
	CW				26.0	66.5	112.5	159.5	205.0	249.0	295.0	346.0		
Yes	CCW	LC	3	1	22.0	64.0	112.5	159.0	202.0	243.0	298.5	340.0	3.7	3.6
	CW				26.0	66.5	115.0	162.5	206.5	246.5	295.5	342.5		
No	CCW	LC	-4	-66	29.0	80.0	129.5	164.0	200.5	239.0	290.5	339.5	4.8	55.8
	CW				26.5	72.5	129.5	164.0	200.0	238.5	283.5	336.5		
Yes	CCW	LC	-3	-24	28.0	79.0	121.0	159.5	201.5	240.5	292.0	339.0	5.1	24.0
	CW				26.5	75.5	124.5	167.5	204.0	242.0	286.5	339.5		
No	CCW	LC	-8	-60	27.0	76.5	121.0	158.5	158.0	238.5	290.0	335.5	8.1	50.5
	CW				21.0	71.0	120.5	165.0	197.0	241.0	289.0	332.0		
Yes	CCW	LC	3	13	25.0	73.0	115.0	152.0	197.0	240.0	295.0	340.0	3.8	13.7
	CW				28.0	73.0	118.5	158.5	196.5	241.0	294.5	339.0		
No	CCW	LC	-36	-50	27.0	73.0	123.0	167.0	203.5	244.5	290.5	334.5	31.7	42.4
	CW				26.0	72.5	128.5	169.0	202.5	243.0	291.5	330.0		
Yes	CCW	LC	-6	-13	28.5	74.0	122.5	160.0	202.5	239.5	292.5	340.0	6.2	15.4
	CW				27.5	73.5	122.5	160.5	201.5	242.5	291.0	337.0		

D	R	CM	IN	IW	Transition Points								CTN	CTW
					NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW		
					22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5		
No	CCW	MS	-12	-22	36.0	77.5	122.5	160.5	198.5	241.0	291.5	343.0	10.7	19.2
	CW				26.0	75.0	123.5	162.0	204.0	242.0	287.0	339.0		
Yes	CCW	MS	0	35	38.0	80.0	125.0	160.0	194.0	236.0	292.5	343.0	2.6	30.1
	CW				30.5	80.0	123.0	162.5	199.0	237.0	288.5	340.0		
No	CCW	MS	-75	-39	40.0	85.5	126.0	150.0	182.0	235.0	287.0	342.0	65.2	34.9
	CW				40.0	86.5	126.0	155.5	187.0	224.5	183.0	347.0		
Yes	CCW	MS	-11	-14	29.0	74.5	120.0	157.0	194.0	237.5	294.0	341.0	10.6	16.4
	CW				25.0	70.0	120.5	159.0	203.0	239.0	293.0	340.0		
No	CCW	MS	-14	-10	22.0	75.5	125.0	164.0	203.0	243.5	290.5	344.5	13.2	13.4
	CW				22.5	66.5	121.0	167.0	204.0	245.0	287.0	335.0		
Yes	CCW	MS	-1	41	29.5	77.0	121.5	254.5	194.0	237.0	292.0	339.5	2.7	37.1
	CW				31.0	75.0	119.0	166.5	196.5	237.5	292.0	242.5		
No	CCW	MS	-37	-74	19.5	70.5	122.5	165.0	203.5	239.5	286.0	328.0	30.5	59.6
	CW				18.0	67.0	125.0	162.5	209.0	245.0	285.0	327.5		
Yes	CCW	MS	22	7	32.0	79.0	122.0	152.0	193.5	234.0	288.0	337.5	18.1	8.9
	CW				27.5	73.0	122.5	156.5	195.5	233.5	291.5	339.0		
No	CCW	MS	1	7	25.0	76.0	123.0	165.0	205.0	244.5	292.5	333.5	2.3	8.3
	CW				26.5	74.0	122.0	161.5	203.0	250.0	292.5	340.5		
Yes	CCW	MS	0	40	32.0	83.0	125.0	157.0	193.0	237.5	290.0	339.5	1.9	37.2
	CW				31.0	81.0	127.0	156.5	201.0	242.0	286.5	345.0		
No	CCW	MS	49	-49	20.0	72.5	118.0	163.0	208.0	246.5	290.0	328.5	42.2	42.7
	CW				20.0	71.5	118.5	158.0	209.5	247.5	292.0	333.5		
Yes	CCW	MS	7	29	34.0	79.0	120.5	158.5	199.5	238.0	287.0	332.0	7.4	26.8
	CW				32.0	79.0	122.5	157.0	198.0	241.0	287.0	334.0		
No	CCW	MS	-57	-28	18.5	67.0	122.0	163.0	202.0	244.5	273.0	333.0	46.6	23.3
	CW				18.0	71.5	122.5	162.0	210.0	254.0	284.0	293.0		
Yes	CCW	MS	-16	23	28.0	71.0	111.0	156.0	201.0	261.5	297.5	340.0	16.2	22.5
	CW				31.0	69.0	112.5	157.0	203.5	247.5	286.5	293.0		
No	CCW	MS	-80	-64	37.5	81.5	119.5	150.0	189.0	230.0	283.0	337.0	69.0	54.5
	CW				16.0	82.5	134.5	169.0	206.5	239.0	281.0	320.0		
Yes	CCW	MS	-8	13	27.5	78.0	126.0	160.5	197.5	238.0	285.5	333.0	10.2	14.4
	CW				27.5	75.5	124.0	158.5	198.5	242.0	284.0	335.0		
No	CCW	MS	-70	-42	28.0	75.0	117.5	164.0	208.0	247.0	289.0	333.5	53.3	34.2
	CW				23.5	71.0	119.5	163.5	208.0	248.5	292.0	335.5		
Yes	CCW	MS	-11	8	29.0	75.0	111.5	161.0	206.0	247.5	293.0	340.5	10.1	10.5
	CW				25.0	71.0	115.5	159.0	202.0	250.5	292.5	338.0		

Averaged over all Lincoln Continentals

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	2.66	2.92	6.41	2.98	-3.30	-4.52	2.17	2.44	1.47
Absolute Average Difference	4.28	4.52	8.22	5.64	5.52	6.08	4.52	4.69	5.43
Standard Deviation	5.02	5.64	9.63	6.77	9.72	7.15	6.22	6.32	7.06
Convergence Error	3.88	2.41	2.19	3.41	4.91	2.78	3.28	3.31	3.27

Averaged over all Mark VII's

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	5.18	7.96	9.10	5.13	-2.24	-5.71	-6.75	-5.65	0.88
Absolute Average Difference	6.74	8.07	9.24	6.68	5.24	7.21	7.17	9.21	7.44
Standard Deviation	8.13	9.42	10.13	16.92	6.87	8.95	19.15	19.75	12.42
Convergence Error	3.75	2.86	2.42	8.08	4.53	4.31	8.67	13.97	6.07

Averaged over all Un-Demagnetized Cars

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	2.59	4.91	8.72	4.21	-1.90	-4.15	-4.81	-1.99	0.95
Absolute Average Difference	5.00	6.00	9.31	5.59	6.19	6.21	8.16	6.46	6.61
Standard Deviation	6.63	7.80	10.62	6.33	10.20	8.21	19.97	9.97	9.97
Convergence Error	4.35	3.12	2.74	4.06	6.26	4.59	9.26	7.21	5.20

Averaged over all Demagnetized Cars

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	5.40	6.26	6.94	4.03	-3.57	-6.15	-0.29	-1.71	1.36
Absolute Average Difference	6.16	6.79	8.21	6.79	4.54	7.15	3.68	7.71	6.38
Standard Deviation	7.06	7.94	9.12	17.50	5.89	8.10	5.09	18.75	9.93
Convergence Error	3.26	2.18	1.88	7.71	3.15	2.59	3.00	10.71	4.31

Averaged over all Lincoln Continentals that were not Demagnetized

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	2.25	2.22	7.06	4.53	-3.72	-3.34	2.22	0.84	1.51
Absolute Average Difference	3.88	4.28	8.31	5.34	6.72	6.47	4.91	4.78	5.59
Standard Deviation	4.24	5.56	10.31	6.32	12.28	7.90	6.53	5.82	7.37
Convergence Error	4.25	3.06	2.50	3.44	7.56	4.06	3.31	4.06	4.03

Averaged over all Lincoln Continentals that were Demagnetized

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	3.06	3.63	5.75	1.44	-2.88	-5.69	2.13	4.03	1.43
Absolute Average Difference	4.69	4.75	8.13	5.94	4.31	5.69	4.13	4.59	5.28
Standard Deviation	5.69	5.73	8.90	7.20	6.16	6.32	5.89	6.78	6.58
Convergence Error	3.50	1.75	1.88	3.38	2.25	1.50	3.25	2.56	2.51

Averaged over all Mark VII's that weren't Demagnetized

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	2.89	7.31	10.19	3.92	-0.28	-4.86	-11.06	-4.50	0.45
Absolute Average Difference	6.00	7.53	10.19	5.81	5.72	5.97	11.06	7.94	7.53
Standard Deviation	8.19	9.36	10.89	6.34	7.91	8.48	26.75	12.56	11.31
Convergence Error	4.44	3.17	2.94	4.61	5.11	5.06	14.56	10.00	6.24

Averaged over all Mark VII's that were Demagnetized

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	7.47	8.61	8.00	6.33	-4.19	-6.56	-2.44	-6.81	1.30
Absolute Average Difference	7.47	8.61	8.28	7.56	4.75	8.44	3.28	10.47	7.36
Standard Deviation	8.08	9.49	9.30	23.08	5.65	9.40	4.25	24.96	11.78
Convergence Error	3.06	2.56	1.89	11.56	3.94	3.56	2.78	17.94	5.91

A 4.2 Precalibration

A 4.2.1 Lincoln Continentals with Annis Demagnetizer

1. Two Lincoln Continentals were demagnetized using the new, more powerful demagnetizer from Annis Corp. The field at the surface of the unit was 450 Gauss (vs. 60 Gauss before).
2. The cars were measured for accuracy of their compass readings and then the compasses were switched, their accuracy measured again, without recalibration.

Key to Symbols	Key to Responses
D – Demagnetization	Yes or No
R – Rotation of Car	CCW – Counter-Clockwise
	CW – Clockwise
CM – Car Model	LC – Lincoln Continental
	MS – Mark VII
NNE – Transition Point Heading	To the nearest Half Degree
ENE – Transition Point Heading	To the nearest Half Degree
ESE – Transition Point Heading	To the nearest Half Degree
SSE – Transition Point Heading	To the nearest Half Degree
SSW – Transition Point Heading	To the nearest Half Degree
WSW – Transition Point Heading	To the nearest Half Degree
WNW – Transition Point Heading	To the nearest Half Degree
NNW – Transition Point Heading	To the nearest Half Degree
Switched	If Compass Switched

D	R	CM	Transition Points								Switched
			NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	
			22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5	
Yes	CCW	LC	20.5	58.0	110.0	160.0	205.0	248.0	296.0	337.0	No
Yes	CCW	LC	21.5	70.5	113.5	158.5	204.0	246.0	293.0	336.0	No
Yes	CCW	LC	35.0	73.0	109.0	146.0	192.0	245.0	307.0	343.0	Yes
Yes	CCW	LC	8.0	58.0	125.0	174.0	213.0	249.0	293.0	325.5	Yes

Averaged over all Cars

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	-1.25	-2.63	1.88	2.13	1.00	-0.50	4.75	-2.13	0.41
Absolute Average Difference	7.50	6.88	4.88	7.88	6.25	1.50	4.75	4.88	5.56
Standard Deviation	9.64	7.41	6.63	10.15	7.57	1.66	7.47	6.65	7.15

Averaged over all Cars before Compasses Switched

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	-1.50	-3.25	-0.75	1.75	2.00	-0.50	2.00	-1.00	-0.16
Absolute Average Difference	1.50	6.25	1.75	1.75	2.00	1.00	2.00	1.00	2.16
Standard Deviation	1.58	7.04	1.90	1.90	2.06	1.12	2.50	1.12	2.40

Averaged over all Cars after Compasses Switched

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	-1.00	-2.00	4.50	2.50	0.00	-0.50	7.50	-3.25	0.97
Absolute Average Difference	13.50	7.50	8.00	14.00	10.50	2.00	7.50	8.75	8.97
Standard Deviation	13.54	7.76	9.18	14.22	10.50	2.06	10.26	9.33	9.61

A 4.2.2 Mark VII's with Lab-Built Demagnetizer

1. Two Mark VII's were demagnetized using the newer, more powerful, demagnetizer that was built in the lab. The field at the surface of the unit was about 430 Gauss, but the working area was large.
2. The cars were measured for accuracy of their compass readings as before. Then the compasses were switched, and their accuracy measured again, without re-calibration.

Key to Symbols	Key to Responses
D – Demagnetization	Yes or No
R – Rotation of Car	CCW – Counter-Clockwise
	CW – Clockwise
CM – Car Model	LC – Lincoln Continental
	MS – Mark VII
NNE – Transition Point Heading	To the nearest Half Degree
ENE – Transition Point Heading	To the nearest Half Degree
ESE – Transition Point Heading	To the nearest Half Degree
SSE – Transition Point Heading	To the nearest Half Degree
SSW – Transition Point Heading	To the nearest Half Degree
WSW – Transition Point Heading	To the nearest Half Degree
WNW – Transition Point Heading	To the nearest Half Degree
NNW – Transition Point Heading	To the nearest Half Degree
Switched?	If Compass Switched

D	R	CM	Transition Points								Switched?
			NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	
			22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5	
Yes	CCW	MS	25.0	78.0	127.5	166.5	202.5	240.0	280.0	330.0	No
	CW		27.0	85.0	130.0	167.0	205.0	240.0	289.0	340.0	
Yes	CCW	MS	29.5	73.5	118.0	155.0	197.5	240.0	285.5	335.0	No
	CW		26.5	79.0	124.5	160.0	197.0	239.5	285.0	337.0	
Yes	CCW	MS	26.5	79.5	129.0	162.0	200.0	234.0	277.5	327.5	Yes
	CW		29.0	86.0	132.0	171.0	207.0	240.5	277.5	327.5	
Yes	CCW	MS	30.0	69.0	114.0	152.5	195.0	244.0	292.5	331.5	Yes
	CW		30.0	75.0	116.5	157.0	196.5	247.0	297.0	345.0	

Averaged over all Cars before Compasses Switched

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	4.50	11.38	12.50	4.63	-2.00	-7.63	-7.63	-2.00	1.72
Absolute Average Difference	4.50	11.38	12.50	5.88	3.25	7.63	7.63	3.25	7.00
Standard Deviation	4.78	12.09	13.28	6.78	3.92	7.63	8.27	4.15	7.61
Convergence Error	2.50	6.25	4.50	2.75	1.50	0.25	4.75	6.00	3.56

Averaged over all Cars after Compasses Switched

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	6.38	9.88	10.38	3.13	-2.88	-6.13	-6.38	-4.63	1.22
Absolute Average Difference	6.38	9.88	10.38	5.88	5.13	6.13	8.63	8.38	7.59
Standard Deviation	6.53	11.67	12.95	7.55	5.45	7.81	10.84	8.55	8.92
Convergence Error	1.25	6.25	2.75	6.75	4.25	4.75	2.25	6.75	4.38

Averaged over all cars, CCW only

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	5.25	7.50	9.63	1.50	-3.75	-8.00	-8.63	-6.50	-0.38
Absolute Average Difference	5.25	7.50	9.63	5.25	3.75	8.00	8.63	6.50	6.81
Standard Deviation	5.65	8.55	11.51	5.76	4.68	8.76	10.37	7.04	7.79

Averaged over all cars, CW only

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	5.63	13.75	13.25	6.25	-1.13	-5.75	-5.38	-0.13	3.31
Absolute Average Difference	5.63	13.75	13.25	6.50	4.63	5.75	7.63	5.13	7.78
Standard Deviation	5.80	14.47	14.55	8.35	4.82	6.51	8.86	6.38	8.72

A 4.2.3 Pitfalls of Precalibration

Three Mark VII's were calibrated and then their compasses switched around between them. Six sets of data were therefore taken. The Annis Demagnetizer was used previous to calibration.

Key to Symbols	Key to Responses
D – Demagnetization	Yes or No
R – Rotation of Car	CCW – Counter-Clockwise CW – Clockwise
CM – Car Model	LC – Lincoln Continental MS – Mark VII
NNE – Transition Point Heading	To the nearest Half Degree
ENE – Transition Point Heading	To the nearest Half Degree
ESE – Transition Point Heading	To the nearest Half Degree
SSE – Transition Point Heading	To the nearest Half Degree
SSW – Transition Point Heading	To the nearest Half Degree
WSW – Transition Point Heading	To the nearest Half Degree
WNW – Transition Point Heading	To the nearest Half Degree
NNW – Transition Point Heading	To the nearest Half Degree
Switched?	If Compass Switched

The method of demagnetization is very important. If done incorrectly precalibration will not work. In this set we demagnetized with a unit that had a small working area. Also, we did not move it across the metal in any uniform or consistent way. Consequently, precalibration did not work. There were about two quadrant shifts for each car. This is clearly unsatisfactory performance. The conclusion is that the demagnetization procedure must be very uniform and reproducible in order to allow compass precalibration to work.

The data is clear enough when left in its' raw form, see below:

D	R	CM	Transition Points								Switched?
			NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	
			22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5	
Yes	CCW	MS	25.0	79.0	122.5	159.5	202.5	241.5	283.0	326.0	Yes
	CW		24.5	83.0	133.0	168.0	208.5	245.0	285.0	332.0	
Yes	CCW	MS	48.0	97.0	133.0	148.0	175.0	222.0	281.5	339.5	Yes
	CW		51.0	107.0	142.0	160.0	184.0	222.0	286.0	351.5	
Yes	CCW	MS	20.0	57.5	109.5	157.5	207.5	255.0	290.0	335.0	Yes
	CW		22.5	62.0	110.0	165.0	217.0	256.5	298.5	340.0	
Yes	CCW	MS	4.0	50.0	109.5	167.0	230.0	263.5	297.5	325.0	Yes
	CW		12.0	55.5	112.5	175.0	230.5	265.0	302.0	330.0	
Yes	CCW	MS	42.0	107.0	125.5	154.0	178.0	213.5	272.0	332.5	Yes
	CW		44.5	115.0	134.0	165.0	192.0	221.0	286.0	335.0	
Yes	CCW	MS	40.0	85.0	125.0	155.0	194.5	231.0	283.5	337.5	Yes
	CW		45.0	90.0	135.0	162.5	203.0	242.0	289.0	345.0	

A 4.3 **Compass Sensor Relocation**

1. A Mark VII with moon roof was used to assess the possible places where the sensor could be moved to without compromising the compass performance.
2. The sensor was put on the end of a long cable, securely fastened to the car at a candidate position, and then calibrated in the open parking lot. Next, the accuracy of the compass was measured as usual. No demagnetization was performed because its' only usefulness is in precalibration, here we were only interested in if the compass worked.

Key to Symbols	Key to Responses
Position	Mounting position of Sensor
D – Demagnetization	Yes or No
R – Rotation of Car	CCW – Counter-Clockwise
	CW – Clockwise
CM – Car Model	LC – Lincoln Continental
	MS – Mark VII
NNE – Transition Point Heading	To the nearest Half Degree
ENE – Transition Point Heading	To the nearest Half Degree
ESE – Transition Point Heading	To the nearest Half Degree
SSE – Transition Point Heading	To the nearest Half Degree
SSW – Transition Point Heading	To the nearest Half Degree
WSW – Transition Point Heading	To the nearest Half Degree
WNW – Transition Point Heading	To the nearest Half Degree
NNW – Transition Point Heading	To the nearest Half Degree

Position	D	R	CM	Transition Points							
				NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW
				22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5
Center	No	CCW	MS	19.5	73.0	110.0	148.0	191.5	238.0	283.0	332.5
Trunk		CW		27.0	78.0	120.5	156.0	197.0	240.0	290.0	334.0
Off-Center	No	CCW	MS	17.0	59.0	107.0	153.0	198.0	243.5	286.0	334.0
Trunk		CW		22.5	67.0	115.0	160.0	208.5	246.0	290.0	334.0
Center Trunk	No	CCW	MS	8.0	40.0	78.0	124.0	170.0	235.0	299.0	337.0
Metal Enclosed		CW		8.0	40.0	78.0	124.0	170.0	235.0	299.0	337.0
Gas	No	CCW	MS	22.5	88.0	127.0	162.0	207.0	245.5	292.0	319.0
Intake		CW		30.0	90.0	140.0	168.0	212.0	247.0	286.0	330.0
Mirror	No	CCW	MS	31.0	70.0	101.0	129.0	180.0	237.0	287.0	330.0
Base		CW		27.0	75.0	108.0	145.0	190.0	240.0	298.0	338.0

Center Trunk

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	0.75	8.00	2.75	-5.50	-8.25	-8.50	-6.00	-4.25	-2.63
Absolute Average Difference	3.75	8.00	5.25	5.50	8.25	8.50	6.00	4.25	6.19
Standard Deviation	3.82	8.38	5.93	6.80	8.70	8.56	6.95	4.32	6.68

Off-Center Trunk

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	-2.75	-4.50	-1.50	-1.00	0.75	-2.75	-4.50	-3.50	-2.47
Absolute Average Difference	2.75	4.50	4.00	3.50	5.25	2.75	4.50	3.50	3.84
Standard Deviation	3.89	6.02	4.27	3.64	5.30	3.02	4.92	3.50	4.32

Center Trunk , Metal Enclosed

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	-14.5	-27.5	-34.5	-33.5	-32.5	-12.5	6.5	-0.50	-18.63
Absolute Average Difference	14.5	27.5	34.5	33.5	32.5	12.5	6.5	0.50	20.25
Standard Deviation	14.5	27.5	34.5	33.5	32.5	12.5	6.5	0.50	20.25

Gas Intake

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	3.75	21.50	21.00	7.50	7.00	-1.25	-3.50	-13.00	5.38
Absolute Average Difference	3.75	21.50	21.00	7.50	7.00	1.25	3.50	13.00	9.81
Standard Deviation	5.30	21.52	21.98	8.08	7.43	1.46	4.61	14.12	10.56

Mirror Base

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	6.50	5.00	-8.00	-20.50	-17.5	-9.00	0.00	-3.50	-5.88
Absolute Average Difference	6.50	5.00	8.00	20.50	17.5	9.00	5.50	4.00	9.50
Standard Deviation	6.80	5.59	8.73	22.01	18.2	9.12	5.50	5.32	10.16

A 4.4 **On-Line Calibration**

1. Both types of car, Mark VII and Lincoln Continental, were demagnetized and calibrated North on the final North line, just before the headlight alignment. Degaussing was done for 30 seconds with the air-core coil.
2. After the cars got through the dyno tests and subsequent repairs, they were calibrated West on the FIR line, heading West. Later on, the car was taken outside and tested as usual.

Key to Symbols	Key to Responses
D – Demagnetization	Yes or No
R – Rotation of Car	CCW – Counter-Clockwise CW – Clockwise
CM – Car Model	LC – Lincoln Continental MS – Mark VII
IN – Null Current Required in North Calibration	One unit is 56.8 μ A
IW – Null Current Required in West Calibration	One unit is 56.8 μ A
NNE – Transition Point Heading	To the nearest Half Degree
ENE – Transition Point Heading	To the nearest Half Degree
ESE – Transition Point Heading	To the nearest Half Degree
SSE – Transition Point Heading	To the nearest Half Degree
SSW – Transition Point Heading	To the nearest Half Degree
WSW – Transition Point Heading	To the nearest Half Degree
WNW – Transition Point Heading	To the nearest Half Degree
NNW – Transition Point Heading	To the nearest Half Degree
CTN – Calibration time for North	To the Nearest 0.1 sec.
CTW – Calibration time for West	To the Nearest 0.1 sec.

D	R	CM	IN	IW	Transition Points								CTN	CTW
					NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW		
					22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5		
Yes	CCW	LC	-6	9	-14.0	50.0	126.5	191.5	236.5	257.5	278.0	304.0	6.8	10.3
	CW				-19.0	56.5	135.0	196.0	236.5	254.5	277.5	304.5		
Yes	CCW	LC	1	-11	5.0	50.5	120.0	184.5	222.5	251.5	286.0	325.0	4.1	11.7
	CW				7.5	58.0	121.5	184.5	231.0	255.0	287.5	324.5		
Yes	CCW	LC	10	10	-9.0	58.0	144.0	195.0	237.0	248.5	278.0	310.0	10.3	11.2
	CW				-6.0	65.5	147.5	206.0	237.5	251.5	275.0	292.0		
Yes	CCW	MS	0	9	4.0	60.0	121.0	173.0	211.5	255.5	297.0	331.5	2.9	10.7
	CW				6.5	54.0	119.0	179.5	223.5	260.5	296.5	332.0		

Averaged over all Data

Kind of Error Measure	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Avg
Signed Average Difference	-25.63	-10.94	16.81	31.25	27.00	6.81	4.44	-22.06	3.46
Absolute Average Difference	25.63	10.94	16.81	31.25	27.00	6.81	18.94	22.06	19.93
Standard Deviation	27.36	11.93	19.91	32.75	28.42	7.68	31.73	26.05	23.23
Convergence Error	3.25	6.88	3.88	5.50	5.25	3.63	26.13	4.88	7.42