

Site-Specific Management Guidelines

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GNSS-Based Auto-Guidance in Agriculture

Summary

Auto-guidance, also called auto-steer, of tractors and self-propelled agricultural machines that is based on a global navigation satellite system (GNSS) represents one currently available technology that can provide significant benefits for crop production in diverse growing environments. Once producers use auto-guidance equipment, they seldom want to return to conventional practices. Newer, improved versions of auto-guidance products provide better operation functionality, which prevents the frustration and fears that early adopters experienced. There is an on-going effort to define and quantify performance of auto-guidance systems so that users of this technology could better select the most suitable option for a given farm operation.

Introduction

The idea of automated guidance of agricultural vehicles is not new. It has been under development since the 1920s when primitive mechanical systems were installed to steer tractors along a desired path. Later, a variety of local triangulation systems allowed implementation of electronics to make such guidance more reliable and applicable in diverse conditions. Additional innovations have involved vehicle guidance with respect to row crops using laser sensors, mechanical feelers, and machine vision approaches.

The benefits of GNSS-based guidance include reduced skips and overlaps, ability to work in conditions of poor visibility (e.g., nighttime, fog, etc.), ability to skip certain areas and then return later with no overlap penalties, negligible setup and service time, ease of use, and event logging. Today, numerous farmers have suspended the use of conventional markers from their operations and rely on cost-effective alternative methods to steer their farm equipment based on continuously measured geographic coordinates.

There are three levels of automation for steering an agricultural vehicle: 1) navigation aids, 2) auto-guidance, and 3) field robots. Relatively inexpensive navigation aids, known as parallel tracking devices or, more commonly, lightbars, are being used by operators to visualize their position with respect to previous passes and to recognize the need to make steering adjustments if a measured geographic position deviates from the desired track.

More advanced auto-guidance options include similar capabilities with the additional option of automatically steering the vehicle using either an integrated electro-hydraulic control system or a mechanical steering device installed inside the cab. With current auto-guidance technology, the operator takes control of the steering during turns and other maneuvers and the auto-guidance system

steers the vehicle across the field. Future auto-guidance systems may actually automate the headland turns as well.

Finally, with autonomous vehicles, the operator's presence on board is not required, and the entire operation is controlled remotely (via wireless communication) or in robotic mode. This can be beneficial, for example, when applying chemicals that are hazardous to human health or when operating on dangerous terrain. The greatest liability of autonomous vehicles is their uncontrolled response in unusual field situations, which has been the major drawback of robotic agriculture. Therefore, auto-guidance has been recognized as the most promising option for today's farming operations.

After browsing through information from different vendors of auto-guidance systems, producers can purchase either factory-installed or after-market equipment packages with costs ranging between \$5,000 and \$35,000, which typically include: positioning sensor (GNSS receiver), controller, user interface module, attitude sensors (vehicle orientation in space), steering feedback sensors, and a steering actuator. The most expensive systems also include a base station (or access to the signal transmitted by a permanent base station installed in the area) required for the ultimate level of steering precision, RTK (real-time kinematic). Generally, the more expensive products involve positioning sensors with greater accuracy, better compensation for unusual vehicle attitude caused by rolling terrain, and more advanced control algorithms.

GNSS Options

As with any application of GNSS, the ability to accurately determine geographic coordinates is essential to assure quality performance. Currently, there are several different GNSS systems either in use or under development. The most prominently known are the Global

Positioning System (GPS, USA), GLObal NAVigation Satellite System (GLONASS, Russian Federation), and European Navigation Satellite System (GALILEO, European Union, still under development).

Despite the type of system used, the radio signals from the satellites that are processed by receivers can be affected by several factors (atmospheric interference, configuration of satellites in the sky, time estimation uncertainties, etc.) that can degrade the quality of the position estimates. To improve the accuracy of estimated geographic coordinates in real time, various differential correction services may be used. Each differential correction system relies on a base station receiver or network of receivers at a known location(s). GNSS errors are calculated at the base station(s) and transmitted in real time to the roving receivers either directly through land-based radio transmission or via a communications satellite (**Figure 1**).

In addition to the differential correction, most receivers apply various signal filtering techniques to assure the best possible prediction of antenna location. Based on the quality of differential correction and internal signal processing, positioning receivers used for auto-guidance have been advertised according to the level of anticipated accuracy: sub-meter, decimeter, and centimeter.

Widely used in agriculture and other industries, single-frequency receivers with sub-meter level accuracy usually rely on one of several alternative differential correction services provided by public and private entities. Popular in the past, the ground-based Coast Guard differential correction AM radio signal (known more commonly as Beacon) is broadcasted through a network of towers located near navigable waterways. The future of this system is somewhat uncertain given the more recent development of the satellite-based Wide Area Augmentation System (WAAS) by the Federal Aviation Administration. The European Geostationary Navigation Overlay Service (EGNOS) operated by the European Space Agency is an analogous system to WAAS for the countries of the European Union. Similar in nature, worldwide services are available through sources such as the free-of-charge John Deere StarFire 1 (SF1) and subscription-based OmniSTAR Virtual Base Station (VBS) signals.

To achieve decimeter level accuracy, dual-frequency receivers can be used with subscription-based John Deere StarFire 2 (SF2), OmniSTAR XP, or OmniSTAR HP differential correction services, or with a local base DGPS station. Historically, a local base station was required to implement a RTK differential correction service, which provides the most precise centimeter level of accuracy.

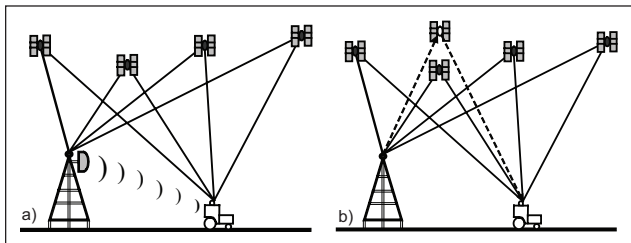


Figure 1. Transmission of differential correction service directly (a), or using a communication satellite (b).

The accuracy of RTK systems will degrade the further the rover moves from the base station – typically about 1 ppm, which is about 1 inch for every 15 miles. In certain locations around the US, local arrays of permanent RTK base stations have been established by private entities or co-op arrangements to provide fee-based coverage of areas with relatively high demand for superior positioning accuracy.

Though commonly called RTK networks, these array systems consist of multiple independent RTK base stations of sufficient spatial density to provide complete coverage and sufficient accuracy in a given area. More recent RTK innovations allow multiple RTK base stations to be networked together to create what is often called a virtual base station at the user's location. This true network arrangement allows base stations to be spaced further apart, but requires much more sophistication in the network management and data communications. In the future, CORS (continuously operating reference stations constructed and maintained by local, state, and federal government agencies) may also have the ability to broadcast corrections to RTK-level receivers located in that area.

GNSS Precision and Accuracy

Positioning accuracy claims listed in current advertisement literature frequently originate from a short-term dynamic test (often referred to as pass-to-pass accuracy) or a long-term static test (sometimes referred to as year-to-year accuracy). Except for RTK-level receivers, pass-to-pass error claims are significantly lower than the year-to-year error estimates. This is important especially when attempting field operations which require coming back to exact locations at different times. For example, when implementing controlled traffic, strip tillage, or other similar management, it is necessary to conduct a new operation in strict geometrical relationship to previous tracks.

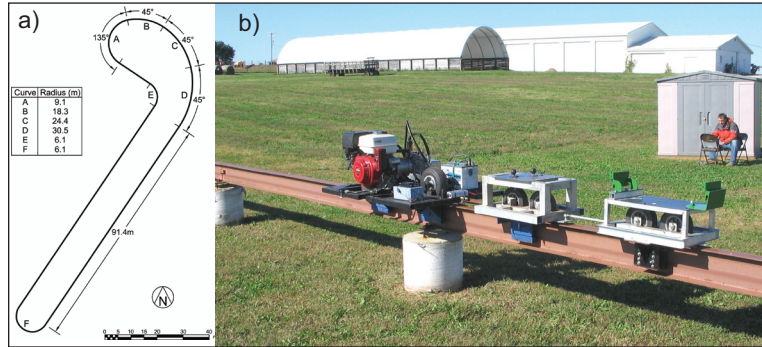
On the other hand, many conventional field operations (e.g., tillage, chemical application, small grain harvesting) are performed according to a travel pattern in which consecutive parallel passes are made with a fixed swath width and a certain level of tolerance can be accepted in terms of long-term position estimate drifts. Therefore, frequently emphasized pass-to-pass error estimates can be related to the expected skips and overlaps between two passes occurring within a 15-minute time period. In most instances, the claimed level of error should not be exceeded 95% of the time. However, the exact definition of pass-to-pass error may vary from vendor to vendor.

As shown in **Table 1**, both pass-to-pass and year-to-year error estimates are mainly affected by the type of differential correction service. The reason for the diversity in available options is that the cost of equipment and services providing the greater level of accuracy is typically highest. However, certain farm operations can tolerate less accurate and, therefore, less expensive selections.

It is also known that the performance of GNSS receivers can be greatly affected by the geometry of satellites in the sky and the quality of signal reception in a given location at certain times. If the number of navigation satellites used to determine geographic location is relatively low (less than 5 or 6) and/or they are not spread around the sky, the position dilution of precision (PDOP) is low and

Table 1. Frequently claimed error estimates.

Option	Correction Source	Pass-to-Pass Accuracy	Year-to-Year Accuracy
Sub-meter	Beacon, WAAS/EGNOS, John Deere SF1, and OmniSTAR VBS	$\pm 15\text{-}33\text{ cm}$ (6-13 in)	$\pm 76\text{-}100\text{ cm}$ (30-39 in)
Decimeter	John Deere SF2, OmniSTAR XP/HP, and Local Base DGPS	$\pm 5\text{-}10\text{ cm}$ (2-4 in)	$\pm 10\text{-}25\text{ cm}$ (4-10 in)
Centimeter	Local Base RTK	$\pm 2.5\text{ cm}$ (1 in)	$\pm 2.5\text{ cm}$ (1 in)

**Figure 2. Shape (a) and test cart (b) of the GNSS receiver test track at the University of Kentucky.**

poor quality performance of any satellite-based positioning device can be expected. Low PDOP can result from an obstacle such as a line of trees at the edge of the field, or simply be due to the time of day when the geometry of satellites in the sky is not favorable for a given location. Likely, the latter can be predicted using several web-based services. Some newer receivers that provide the capability to simultaneously track satellites that belong to different global navigation satellite systems (GPS, GLONASS, and/or GALILEO) would be less likely to suffer from the lack of visible satellites when the view of the sky is partially obstructed.

In addition, it is important to maintain quality reception of the differential correction signal. For example, the Coast Guard beacon signal strength diminishes at a distance range of approximately 300 to 350 km (180 to 220 miles) from the tower. Most satellites used to broadcast satellite-based differential correction signals occupy low latitude geostationary orbits (near the equator), which means that for fields located at northern latitudes, it is important to maintain good visibility of the sky in a southern direction. Keeping the source of the differential correction signal in sight is very important when using a local base station. Signal routers can be used to overcome obstacles such as hills, tall trees, etc. In addition, as follows from above, most manufacturers cannot guarantee superior quality of differential correction at locations more than 10 km (6 miles) away from the base station, which should be considered when developing and/or using a local area array of RTK base stations.

Dynamic Testing of GNSS Receivers

One of the challenges in the GNSS industry is standardized testing and reporting of GNSS accuracy. Much of the performance data that are reported by manufacturers is based on data collected from a static test, i.e., with the receiver fixed in space, usually according to the Institute of Navigation (ION) Standard 101. However, previous research has shown that the static performance of a GNSS receiver is not necessarily indicative of its dynamic performance. Therefore, there is an international effort ongoing to develop a standard for dynamic testing.

The goal of such standardization is to identify procedures and guidelines to test and report the dynamic accuracy of GNSS receivers. The guidelines are specific to the dynamic motions that are typically seen in ground-based agricultural field operations. The standard is intended to be practical to implement at a variety of locations and utilizing a variety of testing techniques while still maintaining equity and repeatability.

At this time, the relevant International Standard Organization (ISO) standard has not been finalized and some of the details may change appreciably. However, once approved, one of the major impacts of the standard will be to

clarify the definitions and methods of calculating several commonly used accuracy parameters such as pass-to-pass accuracy. This will make it much easier to compare the potential performance of GNSS equipment based on consistent manufacturer specifications. The current draft of the standard prescribes test patterns commensurate with ground-based field applications. The test course should include at least 2 parallel straight segments connected by a headland turn. Test speeds should cover the entire range of typical field machinery speeds.

The University of Kentucky maintains a facility for dynamic testing of GNSS receivers. This fixture consists of an I-beam track in the shape shown in **Figure 2a**. A cart system that runs on the track (**Figure 2b**) can carry multiple GNSS receivers simultaneously in either direction and at various speeds.

For an example test, two receivers were evaluated on this fixture. Receiver A was a sub-meter class GPS receiver utilizing WAAS differential correction and Receiver B was a low-cost GPS receiver also utilizing WAAS differential correction, but with an expected accuracy in the range of 2 to 5 m. The receivers were tested for one hour in each direction at a speed of 2.5 m/s. As shown in **Figure 3**, Receiver A was indeed more precise than Receiver B. It was also obvious that the available data output rate of Receiver A was much higher than Receiver B. Closer inspection of Receiver A performance on the straight sections and U-Turn revealed that the positions tend to drift with time. This drift is common to this class of GPS receivers. The receiver also exhibited a slight overshoot performance on the curve.

Potential quantification of results could be extensive as there are a variety of accuracy parameters to calculate. An

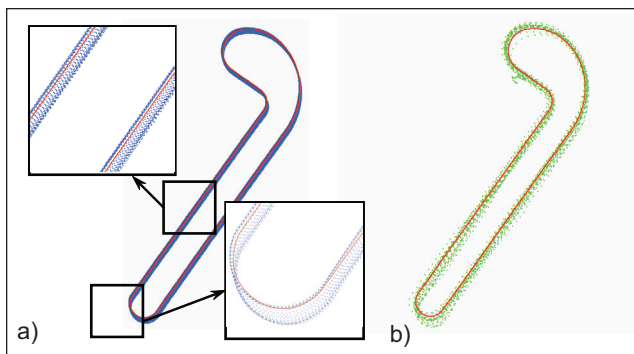


Figure 3. Navigation data records from 2.5 m/s counterclockwise tests of Receiver A (a) and Receiver B (b) shown with the track reference location.

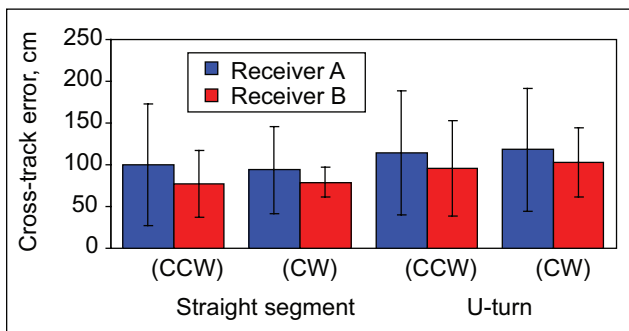


Figure 4. Mean and standard deviation (error bars) of unsigned errors from clockwise (CW) and counterclockwise (CCW) tests of two receivers at 2.5 m/s travel speed.

example comparison of the performance of the two receivers is shown in **Figure 4**.

Overall Performance

When adapting auto-guidance to a particular farm operation, it is necessary to understand that positioning error is just one factor causing less than perfect field performance. In addition, the ability to maintain a desirable geometric relationship between passes is affected by vehicle dynamics, the ability of the field implement to track straight behind the vehicle, and the actual conditions of the field surface (rough, muddy, sloped, etc.).

Currently, hands-free steering of agricultural vehicles is accomplished using either a steering device attached to the steering column or through an electro-hydraulic steering system. An easy-to-setup steering column device can be attached to an existing steering wheel or the steering wheel can be replaced with an actuator module that includes its own steering wheel. Auto-guidance systems integrated with electro-hydraulic steering control circuits alter the travel direction similar to a conventional power steering system where a control valve is used to properly direct hydraulic oil when a steering adjustment needs to be made. When retrofitting old tractors, some manufacturers provide extra hydraulic drive components to guarantee the required steering performance. It is obvious that actuators adjusting direction of travel through a steering column can be less responsive than those that change the orientation of

the vehicle wheels directly. In most instances, a wheel angle sensor is used as a steering feedback sensor in addition to heading data obtained from the GNSS receiver, which makes electro-hydraulic steering systems even more reliable.

Control of vehicle dynamics becomes more challenging when farming sloped ground. The roll (tilt from side-to-side), pitch (tilt from front to back), and yaw (rotation around the vehicle's center of gravity) alter the location of the GNSS antenna with respect to other parts of the vehicle. For example, when driving along a slope, the horizontal position of the antenna located on the top of a cab shifts to one side of the tractor instead of being projected through the center of the tractor. This causes an engaged steering control system to guide the vehicle so that the point directly below the antenna (not the center of the vehicle) follows the desired pass. To compensate for this misalignment, most auto-guidance systems include a combination of gyroscopes and accelerometers or several antennas placed in different locations on the cab. Less advanced terrain compensation modules can only deal with two or three angles, while more sophisticated sensing systems, can measure the total dynamic attitude of the vehicle in space (tilt, roll, and yaw as well as accelerations in each direction).

As mentioned above, vehicle stability and proper alignment of the attached implement are very important when implementing auto-guidance. If a skip followed by an overlap takes place with every alternating pass in the opposite directions during straight and level trips, it is likely that the antenna is not centered with respect to the vehicle, the implement is shifted with respect to the tractor, or known antennae offset is not correctly programmed into the controller. In curved paths, even a properly adjusted implement will not exactly follow the vehicle and track towards the center of the curve. This phenomenon also occurs on a sloped terrain where the implement tends to drift downhill.

Several manufacturers have addressed implement tracking concerns by providing add-on implement steering systems. One such solution allows accurate sensing of the implement's position with respect to the vehicle and mechanical adjustment of this position using a set of large-diameter disc coulters to steer the implement. Additional developments are focused on compensating for known shifts by adjusting the vehicle's trajectory to assure proper tracking of the implement instead of the vehicle. Optical and mechanical crop-based guidance systems can also be useful when it comes to the position of the implement with respect to previously established rows.

Auto-Guidance System Testing

To illustrate the overall performance of several auto-guidance systems for participants of the August 2005 Field Day that took place at the Agricultural Research and Demonstration Center near Mead, Nebraska, a light test cart was equipped with a coulters and a survey-grade RTK-level GPS receiver. Every tractor pulled the test cart along a J-type course starting with a variable radius curved section and continuing into a straight section that contained a portion with significant elevation change. During the return

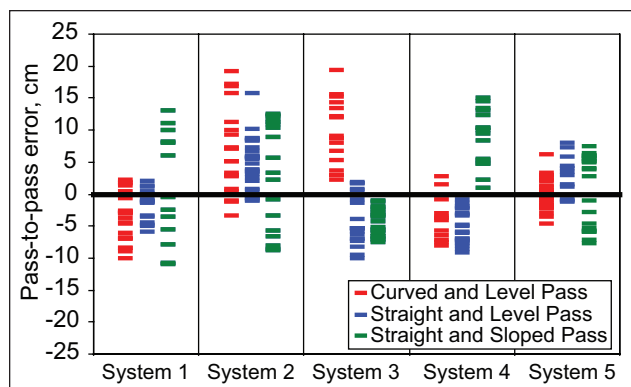


Figure 5. Pass-to-pass error distributions obtained while demonstrating five different RTK-level auto-guidance systems.

pass, every vehicle was operated along the same path in the hands-off steering mode. The marks left by a single shank coultter installed in the center of the cart served as a visual illustrator of the overall performance. To confirm these observations, GPS position records were used to calculate the distance between the two tracks in opposite direction (**Figure 5**). To make the calculations, 20-m (66-ft) long sections were extracted from the: 1) curved path, 2) straight and level path, and 3) straight and flat path.

Certainly, the test cart and the GPS receiver were significant contributors to the errors shown in **Figure 6**. While pursuing a more representative and reliable testing procedure, another series of tests were accomplished using an improved test cart equipped with a linear potentiometer array sensor. This sensor was able to measure the position of triggers placed around the concrete track of the Nebraska Tractor Test Laboratory with 2-cm (0.8-in) accuracy with respect to the center of the cart. As shown in **Figure 6**, this method allowed summarizing errors estimated for a pair of systems with two levels of accuracy (centimeter and decimeter). As mentioned earlier, the RTK-level centimeter system was found to be immune to time drifts and provided the same estimate for short-term and long-term errors, while the dual-frequency DGPS-level decimeter system presented higher long-term errors.

Similar to the field demo, it was observed that linear potentiometer sensor uncertainties together with inconsistent

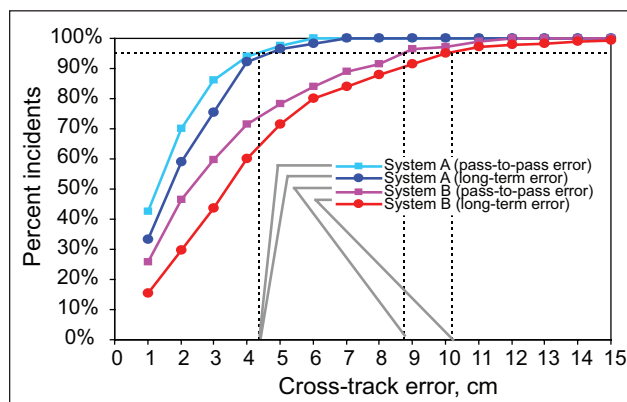


Figure 6. Comparing error estimates for a centimeter-level System A and a decimeter-level System B using the linear potentiometer sensor.

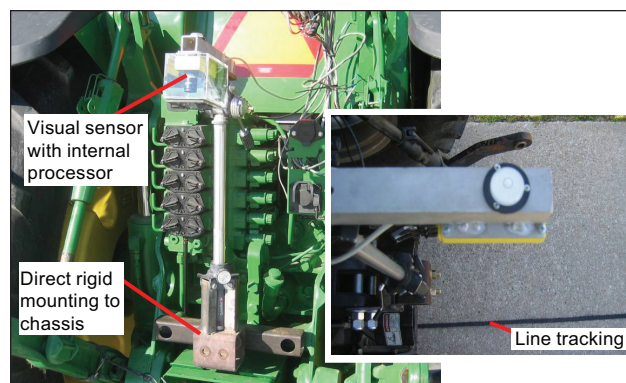


Figure 7. Visual sensor-based auto-guidance testing system.

test cart tracking and vehicle dynamics delay increased the observed errors when compared to corresponding manufacturer claims. Recently a newer concept for quantifying auto-guidance errors based on a visual sensor system has been developed (**Figure 7**). In this case, distance between passes made over the same track in the opposite direction (cross-track error) was measured relative to the tractor chassis and with less than 2-mm resolution. As illustrated in **Figure 8**, both pass-to-pass and long-term errors determined using this visual sensor system were significantly affected by tractor travel speed. An international group of manufacturers, researchers, and customers was formed to create a standard that will define guidance error terms and provide basic codes for future tests.

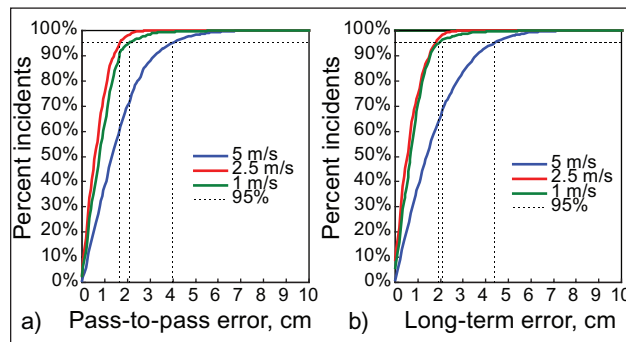


Figure 8. Cumulative distribution of unsigned pass-to-pass (a) and long-term (b) errors measured using the visual sensor system.

System Selection Guidelines

Another important feature of any auto-guidance system is its ease of use and set-up. This includes speed of initialization, input of implement and tractor parameters, and traffic pattern selection. Many systems now come with newer 3-D graphical displays and a large selection of traffic patterns. The displays range from a very intuitive colorful graphic touch-screen display to older menu driven hard-key units with limited graphical feedback and numerical displays. Newer units also have the ability to combine two or more types of traffic (such as a straight A-B line with an adaptive curve) to operate correctly in odd-shaped fields or when obstacles are present (trees, utility poles, etc.).

Although every system can easily perform straight line patterns, some products have difficulty in steering vehicles

along contours (such as field terraces). This is especially true for older GNSS units that can determine geographic locations only every 0.2 to 1 s. In high speed applications, e.g., spraying, this frequency may not be sufficient to produce a smooth curve. However, with newer high-frequency units, vehicles can be operated following curved paths while traveling with speeds up to 50 km/h (31 mph).

Current auto-guidance control systems may comprise either a single box or multiple pieces of electronics installed around the cab. The more complex units are less transferable from one vehicle to another as compared to the single-box options. However, these compact units may be limited in terms of supported level of accuracy. In addition,

the more advanced equipment can be used to control spraying rate, adjust seed population, record yield-related measurements, or implement other precision agriculture practices. Versatility of such units provides an advantage of spreading the cost among different practices.

Finally, when selecting lower-level systems, it is important to verify feasibility of their upgrades. While some hardware components have limited applicability, other parts can be reused when stepping up from lower end to more precise auto-guidance options. It has been noted that some producers start with a relatively inexpensive solution and simply upgrade it when a more sophisticated option is found justifiable for their operation. ■

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