



POWER GENERATION

Fully-Variable Fan Drives

The Benefits of Fully-Variable Fan Drives on Generator Sets



Introduction

Executive Summary

Technologies from the on-highway vehicle markets, designed to reduce fuel consumption, noise and pollutants, are slowly migrating to other applications and industries. The latter includes the power generation market, inclusive of stationary and mobile generator sets. While fully-variable fan drives are proven and standard equipment on heavy-duty commercial vehicles (e.g. semi-trucks), as a means to reduce fuel consumption and noise, they are not standard on generator sets. Moreover, their effect on generator set operation has not been deeply studied. The goals of this study were to determine if a fully-variable fan drive cooling system could reduce fuel consumption and noise on a 100kW generator set and whether those results might be extrapolated to other generator sets. A positive finding could help inform future generator set designs and options and by extension, provide economic and environmental benefits to entities employing generator sets in various applications and environments.

The approach was to use a 100kW generator set to establish a base line in measuring fuel consumption and noise and then modify that same generator with a fully-variable fan drive. Tests would be conducted in a test cell with variables such as load and ambient temperatures being held constant—and other variables, such as fan blade design and material, homogenized to the extent possible.

The result was that the test generator set, modified with the Horton fully-variable fan drive cooling system, provided significant fuel savings and noise reduction over the same generator set with a standard cooling fan. It is believed this result can be extended to other generator sets, with similar benefits, depending on the application and environment in which the generators operate.

Increasing the fuel efficiency of on-highway vehicles (passenger and commercial) is both a competitive marketing strategy as well as a reaction to legal mandates. One of the more notable legal actions occurred in 1975, with the advent of the Corporate Average Fuel Economy (CAFE) standards. These were, in part, precipitated by the Arab oil embargo (1973-1974) in which gas prices skyrocketed and lines at gas stations were a regular occurrence. On the other hand, since the mid-nineties, environmental considerations have led the U.S. Environmental Protection Agency (EPA) and other similar organizations around the globe, to introduce standards aimed at reducing exhaust gas emissions of diesel engines. These have typically been introduced for on-highway engines first and then migrated to off-highway engines over time. More recently (September 2011), the National Highway Traffic Safety Administration and EPA promulgated the first-ever federal regulations mandating fuel economy improvements for heavy-duty commercial vehicles.

Regardless of the regulations affecting on-highway vehicle fuel economy, fleet operators and private and corporate agricultural operators have long had a vested interest in the fuel consumption of the various vehicles and equipment used in their operations: it has a collective effect on profitability. Accordingly, there are marketing reasons for manufacturers to focus on improving and then promoting the fuel economy of their on- and off-highway equipment. Even in the case of rental equipment providers, who typically do not bear

the burden of fuel costs, there are competitive reasons to select equipment with the highest fuel efficiency.

The use of advanced combustion technologies to achieve higher emission levels, such as EPA's Tier III and Tier IV standards, has led to increased heat rejection from the engines. This, in turn, has necessitated the use of larger cooling systems that can handle this in the harshest of conditions: equipment operating at 100 percent of rated capacity and at the highest ambient temperatures. Although it is not impossible for the equipment to encounter such conditions, it is highly improbable that the equipment would operate under them for a majority of the time. Consequently, the cooling systems are almost always over-sized for the largest duration of the equipment's operational life.

Horton developed a marketable version of its on/off fan clutch in 1966 for Cummins and Detroit Diesel. In 1968, its use was expanded to off-highway applications like mining trucks. As fuel prices started to rise in 1971, Horton's pioneering work with fan clutches had instant appeal for reducing fuel consumption and decreasing noise. More advanced development work by Horton was escalated by the Oil Embargo.

This problem is exacerbated in a generator set where the engine runs at a constant speed (typically 1800 RPM for 60 hertz or 1500 RPM for 50 hertz output frequencies) and the radiator cooling fan is driven directly by the engine. This is because in other equipment, as the engine load is reduced, the engine speed, and consequently, the fan speed are reduced. Yet, a generator engine and cooling fan are always forced to run at a constant speed regardless of the load. In addition, generator sets are rated based on operating conditions: the highest rating is for standby or emergency operation, while prime power and continuous power ratings are much lower, but are geared towards significant operational hours. As a result, cooling systems that are designed for standby ratings are over-sized for prime power or continuous duty operations. These operational conditions are regularly encountered by rental generators used at construction sites and public events, generators used for peak-shaving when utility tariffs are high, and off-grid generator power plants that sell electricity—commonly referred to as Independent Power Producer (IPP) projects.

Another downside of running the cooling fan at a constant speed in a generator set is that in cold weather conditions, it results in over cooling of the engine: a situation where the engine and associated subsystems are unable to achieve sufficient temperature for proper combustion and optimal engine performance. This leads to issues such as the plugging of diesel particulate filters, engine wet-stacking, and frozen crankcase breathers. The latter not only degrades performance but frequently leads to reduced uptime and engine life.

Finally, a significant proportion of the noise produced by a generator set can be attributed to its radiator cooling fan. High noise levels could be a safety concern for personnel in close proximity to the generator,. Yet, noise is always perceived as nuisance, especially in densely populated areas such as urban centers and residential neighborhoods.

A popular approach introduced by Horton (and adopted as standard by the heavy- and medium-duty truck manufacturers in the seventies in the U.S.) was to use an on/off fan drive: a mechanical clutch that would either completely disengage the fan from the engine so that it would not spin, or engage it to spin at full speed. This allowed the fan to spin for a brief period of time to cool the engine and then turn off until the engine needed cooling again. Over time, the

technology was refined to include multi-speed drives, wherein the fan either spun at full speed, or at a lower speed that ensured just a sufficient level of cooling to avoid frequent full engagement. These drives utilized a friction-based clutch that was spring-engaged and pneumatically-disengaged.

More recently, fully variable viscous fan drives are becoming popular because of their inherent capability of spinning the fan at any speed, based on cooling requirements. Additionally, the use of viscous fluid for power transfer eliminates the need for friction liners. The latter renders these drives virtually maintenance free. Another benefit of using fully-variable fan drives, especially in Europe, is that the regulations there allow the equipment's noise rating to be defined at 70 percent of rated fan speed. This is a significant benefit in an era where noise regulations are getting stricter by the day.

Despite considerable advances and adoption in fan drive technology, the benefits of this technology have not been realized or even understood well in many off-highway markets such as generator sets.

The goal of this study is to understand the effect a fully-variable fan drive delivers in terms of fuel economy and noise when installed in a 100kW enclosed rental generator set that would otherwise employ a directly-driven cooling fan. To achieve the goal, this study has the following objectives:

1. Determine the fuel consumption of a conventionally-equipped ("off-the-shelf") 100kW rental generator set, cooled with a direct-drive fan apparatus, at various loads (0%, 25%, 50%, 75% and 100%), and at a set ambient temperature of 67 degrees Fahrenheit (19°C).
2. Determine the fuel consumption of the same generator set, at the same loads but at a set ambient temperature of 87 degrees Fahrenheit (31°C).
3. Determine the fuel consumption of the same generator set, at the same loads (five) and temperatures (two), when the cooling system is modified with a fully-variable fan drive system as opposed to a directly-driven fan blade connected to the drive shaft via a belt.
4. Compare the fuel consumption of the conventionally-cooled generator set to that of the generator set with the modified cooling system, at each load and temperature, to determine whether there is a change in fuel efficiency and whether that change is positive, negative or neutral.
5. Determine the fan speed (in RPMs) of the conventionally-equipped generator set as called for by the generator to provide optimum cooling and as driven by the electrical loads applied.
6. Determine the fan speed (in RPMs) of the modified generator set as called for by the generator to provide optimum cooling and as driven by the electrical loads.

7. Compare the fan speeds, called for by the conventionally-cooled generator set, to that called for by the generator set with the modified cooling system, at the prescribed loads, to determine the difference in speeds under the same conditions.
8. Determine the noise output, as measured in decibels, of each of the fan speeds, from both generators sets, at four fixed points of equal distance from the generator sets: front, back and sides. Average the noise levels of the four points to determine an average noise output figure for each fan speed (RPMs), for each generator set cooling configuration, i.e. standard or modified with a fully-variable fan clutch.
9. Determine the difference between the average noise output of the conventionally-cooled generator set as compared to that of the generator set with the modified cooling system at the various load levels.
10. Draw general conclusions as to the fuel efficiency and noise output of each generator set and whether it can be concluded that one or the other is more fuel efficient and quieter than the other.
11. Extrapolate the results to provide cogent generalizations that can be applied to similar equipment, with the expectation of yielding the same results, positive or negative.

The remainder of this technical paper covers the following:

Related Work	– Prior studies or work in the area
Methodology	– Testing process and procedures
Limitations	– Potential factors in the test process or procedures that may affect findings
Results	– The actual data collected in the respective tests
Summary	– The findings of the test and process
Conclusion	– How manufacturers and others can apply the knowledge gained as part of the test
Future Work	– Testing Horton plans to conduct in future to similar stationary equipment

Related Work

Horton is unaware of previous studies in this area by other authors and/or companies. Yet, an earlier (and less formal) Horton study was the catalyst for this one.

In Horton's previous study, experiments were conducted on a Cummins 200 kW generator set with a QSL9 engine. The goals were similar in that Horton wanted to understand if a fully-variable fan drive system could reduce the generator's

fuel consumption and noise output when compared to the same generator set equipped with the standard, direct-driven cooling fan. In this case, Horton kept the load constant at zero and only varied the fan speeds (on the Horton-modified generator) using an external controller for set intervals. The study showed that using a fan drive, to adjust the fan speed, resulted in significant fuel savings and noise reduction over the standard-equipped generator set. Yet, Horton realized to ensure strong correlation between the results and actual running conditions, it needed to modify the generator set loads and not the fan speed.

Methodology

A 100kW, liquid-cooled rental generator set was obtained from a local, St. Paul, Minnesota distributor. It was in excellent physical and operational condition. The generator set model C100D6R manufactured by Cummins Power Generation featured a Cummins 4.5 liter, turbocharged and charge air cooled, four-cycle, in-line, QSB5-G4 Tier III diesel engine. It was capable of sustaining various loads and had a maximum, standby rating of 100kW, and prime rating of 90kW at 60 hertz.



Generator set in the Horton Chassis Dynamometer Room at Horton

Two series of tests were conducted, with both measuring fan speed and fuel consumption. Tests for noise at various fan speeds and positions around the unit were conducted separately, based on data captured in the two primary tests.

The first set of tests were conducted on the generator as originally equipped by the manufacturer, with the exception that the original fan had been replaced by a Horton MS9 fan to yield similar airflow performance but reduced overhung weight on the engine. The objective of the latter was to try to eliminate as many variables as possible to maintain test integrity. Fan rotation was provided by a belt and pulley mechanism, connected to the main drive shaft of the engine. The measurements were taken with the enclosure closed.

The second set of tests were conducted with a modified cooling system provided by Horton. The direct-drive fan mechanism was dismantled and removed from the generator set. It was replaced with a Horton LCV 40 fan drive. The drive was affixed to the engine block using a Horton bracket. The radiator and related components remained the same. Again, the measurements were taken with the cabinet closed.

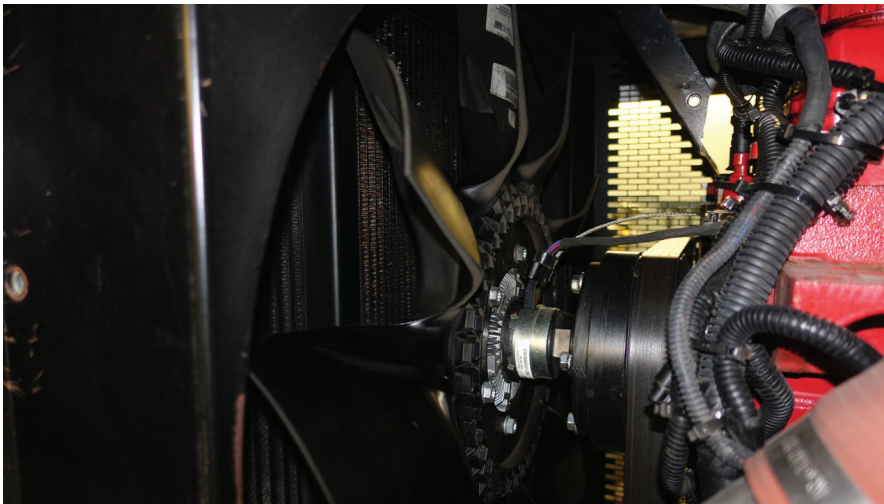
Fuel consumption data was computed using consumption information broadcasted by the engine control unit over the CAN link.

The fuel economy testing was conducted in the chassis dynamometer room at Horton. The room is a suitable for controlled temperature testing of diesel powered equipment.

The noise measurements were conducted on a flat asphalt surface in an open area behind the Horton Technology Center, far away from any structures.

The initial series of tests were run on the generator set with the standard, conventional cooling assembly, as provided by the manufacturer with the original fan replaced with a Horton MS9 fan. The second set of tests were applied to the generator set containing the Horton fan drive modification. In both cases, the following testing procedures applied.

Test 1 – Conventional Direct-Drive Cooling Fan



Generator with LCV 40 Fully-Variable Fan Drive Modification

The first test lasted approximately five hours, with an hour devoted to measurements at each load factor. The loads were as follows: 0%, 25%, 50%, and 75% and 100%. The initial ambient temperature in the test cell was set at 67 degrees Fahrenheit (19°C) and was maintained with little fluctuation.

Test 2 – Conventional Direct-Drive Cooling Fan

In Test 2, all the parameters and procedures were held constant, with the exception of the starting ambient temperature which was set to 87

degrees Fahrenheit (31°C) and then held virtually constant.

Test 3 – Horton Fully-Variable Fan Drive Cooling System

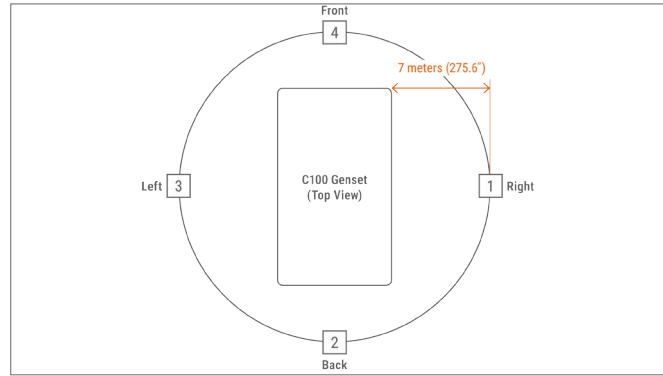
Test 3 and 4 feature the same rental generator set, though modified with Horton’s fully-variable LCV 40 fan drive cooling system. Again, the first test lasted just over five hours in total, from start up to shut down. Further, the same loads were placed on the generator set, for the same hour-long intervals as Test 1 and 2. The ambient temperature in the test cell was again set to 67 degrees Fahrenheit (19°C).

Test 4 – Horton Fully-Variable Fan Drive Cooling System

In Test 4, all the parameters and procedures were held constant with Test 3, with the exception of the ambient temperature which was set to 87 degrees Fahrenheit (31°C).

Sound Measurements, Tests 1 - 4

Fan speeds were captured at all loads for both the direct-drive fan generator



set configuration and the modified Horton fan-drive generator set configuration. Since it is possible to regulate/control the fan speeds in each configuration manually for test purposes, the sound level (dBA) tests could

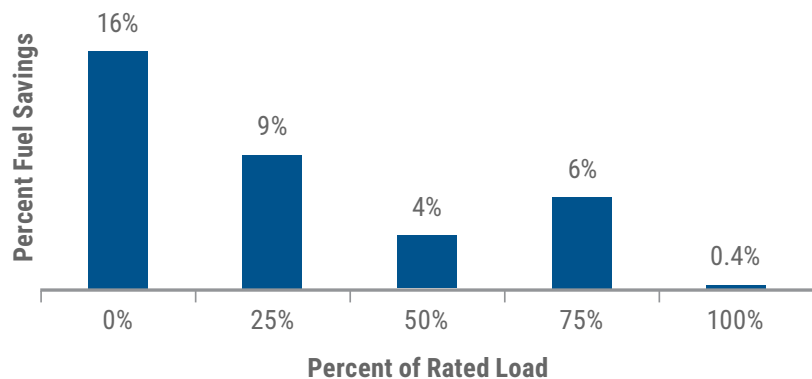
be done independently. The sound was measured from a fixed point of seven meters (275.6") from the back, front and sides of each configuration.

Limitations

1. The results of the test showed some anomalies in terms of cooling performance. While it is clear that fuel savings and noise reduction were benefits of the fully-variable fan drive cooling system, Horton believes the outcome could have been even more positive. At issue, when the original fan was removed and the Horton fan installed, not enough attention was given to the spacing hardware. Thus, the fan was not positioned appropriately in the shroud (too far out). Consequently, cooling was negatively impacted. It is also believed that this circumstance may have resulted in the fuel savings curve not being monotonic.
2. Testing the generator at a much lower temperature such as may be experienced in a winter or arctic climate was not possible but may be a goal for further tests.

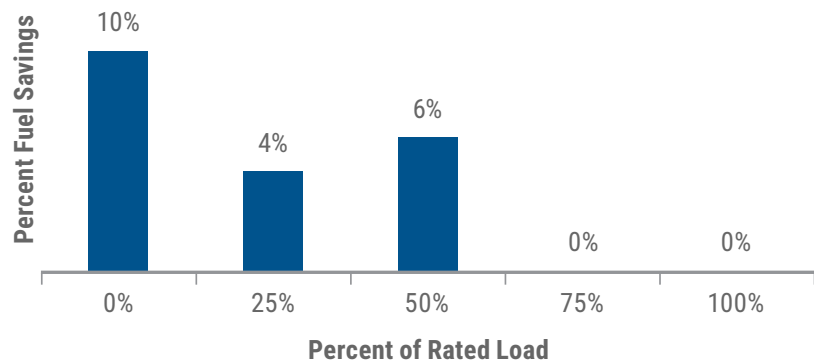
Results

Fuel Savings at Low Ambient Test (60-70°F/16-21°C)



In the low ambient test and at no load, the Horton fully-variable fan drive cooling system provided a 16 percent fuel savings over the non-modified generator set with standard cooling. At 25 percent load, the savings was 9 percent and at 50 percent load, 4 percent. Savings increased at 75 percent load to 6 percent but dropped off significantly at 100 percent load.

Fuel Savings at High Ambient Test (80-90°F/27-32°C)



LCV 40 Fully-Variable Fan Drive

The Horton Modulator® LCV40 features a rear-mounted connector for easy installation. It pairs effectively with a variety of Horton WindMaster® fans and other manufacturers' products. It can help your products run longer, better and quieter, while reducing fuel consumption by:

- Matching engine's precise cooling needs
- Preserving torque and horsepower through lower off-speed
- Dissipating heat with optimized fin design

In the high ambient temperature test and at no load, the Horton fully-variable fan drive cooling system provided a 10 percent fuel savings over the non-modified generator set with standard cooling. At 25 percent load, the savings was 4 percent and at 50 percent load, 6 percent. Savings at 75 and 100 percent loads were zero. The test results were negatively impacted by the sub-optimal fan insertion as described above in the Limitations section.

Summary

Definite Fuel Savings

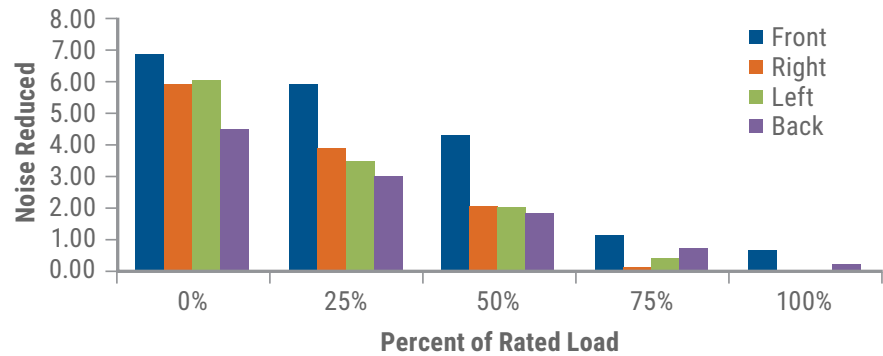
In terms of fuel economy, it is clear that at ambient temperatures between 60 and 70 degrees Fahrenheit (16-21°C) and at various loads, using a fully-variable fan drive in a 100kW generator can result in significant fuel cost savings, especially over time, e.g. a long-term construction project. It is important to note that the fuel savings here manifested with one-hour intervals at each load. While the savings tend to decrease at higher ambient temperatures, they are still significant.

Conversely, it is also possible to hypothesize, with some confidence, that generators of this capacity, running in colder conditions (less than 60°F or 16°C), would also benefit by having a fully-variable fan drive cooling system. In the latter case, not having a constant load on the engine from a fan, when completely unnecessary, would contribute to fuel savings. A fully-variable fan drive would have the added benefit of helping prevent over cooling, thereby contributing to optimized uptime and performance.

Definite Noise Reduction

The results of this study also reveal a significant reduction in noise output when the generator was modified with a fully-variable fan drive instead of the standard cooling fan run off the drive shaft.

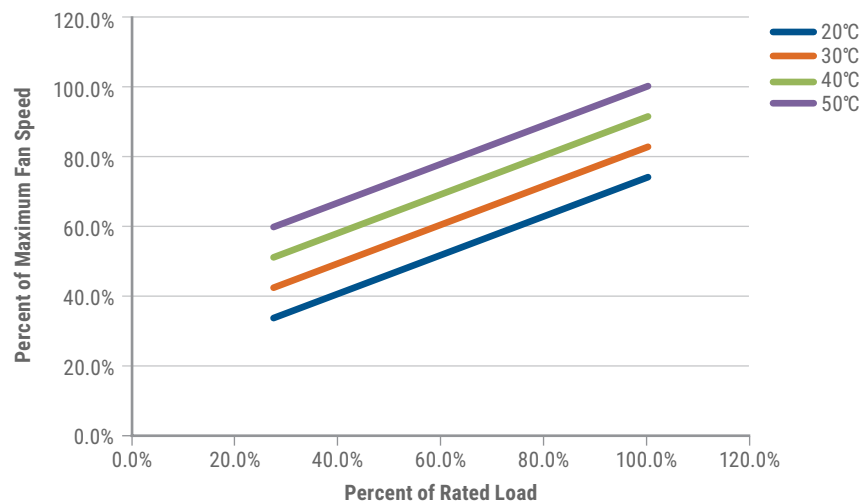
Noise Reduction by Percent of Rated Load at Various Positions



Rule of Thumb

Analysis of the fan speed data showed that, as expected, there is a high correlation to both ambient temperature and load on the equipment. In both cases, the data showed a very linear response.

Correlation of Fan Speed to Ambient Temperature



Above, the data showed that the projected fan speed required for a given load and temperature condition can be predicted relative to the rated temperature and load of the equipment. For example, when the machine is running at 40 percent of rated load and the ambient temperature is 20°C versus the rated temperature of 50°C, the fan is only required to run at 40 percent of full speed. Because fan power has a cubic relation to speed, the fan power at this condition is only 6.4 percent of power required at full fan speed. The relationship can be approximated by the fan speed being reduced by .5 percent for each 1 percent reduction in load from full load and an additional 1 percent for each degree C from rated ambient temperature.

Conclusion

The study was developed to understand whether a fully-variable fan drive would provide fuel and noise output benefits when installed in place of the standard cooling system in a 100kW rental generator set. The study proved that significant fuel savings and noise reductions were possible when the variable fan drive was used.

More significant, perhaps, are the study's implications for future generator set designs. It seems logical to assume that all generator sets could benefit from the fully-variable fan drive in terms of both fuel savings and decreased noise production. It depends on the application and the environment in which the generator set is used.

As an example, an emergency backup power system at a datacenter may not benefit by having its generators equipped with variable fan drives. The reason is the generators are seldom in use, except for exercise or the odd grid or infrastructure failure. In effect, they are not constantly running and thus fuel usage may not be a determining factor.

One or more generators used in rental or IPP applications, however, may benefit by having fully-variable fan drives as standard equipment. There are several examples of multiple generator installations used for prime power in the Middle East, South America, Asia and Africa where the grid is not accessible: these generators are in constant use. Another example, and less remote, are generators used in mining and oil and gas operations. Whether the environments in which the latter operate are hot or cold, a fully-variable fan drive cooling system could reduce fuel consumption and improve uptime and performance in the latter applications.

The generator used in this study was a rental set. It was chosen, in part, because rental generators are typically used (when on onsite) continuously. Fuel conservation, but also uptime and reliability, are key concerns. Noise also becomes an issue when rental units are used near a residential neighborhood and this is often the case in highway or other construction projects.

The recommendation is that generator set manufacturers, their channel partners and rental generator fleet operators examine and consider the benefits of fully-variable fan drives in their generator set applications and by extension, specify the equipment when it is economically or environmentally (e.g. noise) advantageous.

Future Work

Horton will continue to conduct similar tests with different generators and applications. As part of the ongoing research, it anticipates it may conduct a similar study as this one but in a much colder environment.



Manish Virmani

About the Authors

Manish Virmani joined Horton as VP, Global Market Development in March of 2016. Prior to Horton, Virmani spent six years at Cummins Power Generation, in Minneapolis, in a variety of business leadership roles. These included Director of Mission Critical and Prime Power Segments, Marketing and Strategy Leader of Vertical Segments and Senior Product Manager Global Controls. Virmani has significant international market experience in several countries including those in South America, the Middle East and Western and Eastern Europe.



Dave Hennessy

Dave Hennessy has been with Horton for over 26 years. He was hired in May 1990 as a Design Engineer and has held the positions of Lead Design Engineer, Sr. Project Engineer, Design Engineering Supervisor, Design Engineering Manager and Vice President Advanced Development. He currently serves as Vice President, Research & Development. Prior to Horton, Hennessy was with DANA Corporation as a Design Engineer, from 1986-1990.

About Horton

With more than 60 years of industry experience, commitment to service, reliability and innovation, Horton is a premium worldwide provider of fan drives, fans and suspension products for on- and off-highway vehicles and equipment. Horton's comprehensive research and development processes are driven by a dedication to exceed industry requirements today and in the future. The company was awarded the 2014 President's "E" Award for Exporting, the 2013 Minnesota Governor's International Trade Award as well as the U.S. Department of Commerce Export Achievement Certificate. Horton has manufacturing plants in the United States and Germany, with licensed manufacturing facilities in Australia, China and the United Kingdom; offices in the United States, Canada, Mexico and Germany; and representatives in Brazil, Chile, Russia, Japan, South Korea, China, India and Australia.

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