



THE AMAZING Infinite-Ratio 'Gearbox'

This fuel-saving transmission is going into a new Saturn SUV, among other vehicles. At its heart is a very special belt like the one shown here.



No, this isn't a chic necklace but a superstrong steel belt that transmits power from engine to wheels.

Back in 1989 I was piloting a little Subaru minicar called the Justy ECVT through the rowdy traffic on Manhattan's West Side Highway. Spotting an opening ahead in the adjacent lane, I nailed the throttle and began steering to the right. That's when I narrowly missed sideswiping a big Oldsmobile. Time expands a lot at such moments, and as the milliseconds marched by I felt like the captain of a huge ship who had ordered a change of speed. It was as if the first officer had briefly second-guessed my command before relaying it

belowdecks to the crew members in charge of actually opening the steam valves that send power to the propellers. There was an unsettling time lag before the car finally got up and went.

The Justy was equipped with a continuously variable transmission, or CVT, and I was experiencing what engineers at the time called the "rubber-band effect." Justy owners soon learned not to expect acceleration until a second or two after applying the throttle. It took that long for mysterious electrohydraulic hardware under the hood to adjust the transmission's

gear ratios to suit the conditions of the moment. With its tiny 1.2-liter engine and slo-mo throttle response, the Justy ECVT wasn't suited to American driving conditions and in a few years faded from the scene. But the idea of a thrifty transmission with an infinite number of ratios, instead of just a few, stayed alive in engineering labs around the world.

Now there's a new generation of CVTs that really work. They are available in a number of small European and Japanese cars, and U.S. automakers are tooling up to produce them as well. A small CVT-equipped sport-utility vehicle from GM's Saturn division is slated to go into production in the fall of 2001, and more American

by **Stuart F. Brown**

offerings will follow. Once economies of scale kick in, CVTs should cost less to make than the conventional automatic transmissions used in 90% of the vehicles sold in the U.S.

Cars and light trucks with CVTs also consume 6% to 15% less fuel than automatics. Even before the recent spike in gasoline prices, this appealed to companies like GM and Ford, which have seen their federally mandated corporate average fuel economy (CAFE) numbers dragged down by all the thirsty trucks and SUVs and minivans they're selling. Missing the magic CAFE number can cost them stiff fines. And with fuel prices high, the automakers want to be ready if consumers rediscover fuel efficiency.

GM and Ford have recently been in a public-image battle over which company's vehicles will have the better fuel economy—particularly in SUVs—and GM vice chairman Harry Pearce has said CVTs will

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be appearing in some light truck models. Arv Mueller, GM's group vice president for powertrains worldwide, told *FOR TUNE*, "We think the CVT is a really cost-effective way to get a big chunk of fuel economy, and in this business you'd kill for half a percent. We're thrilled with the performance and the feeling of it."

The new generation of CVTs is just one of several technologies auto engineers have in their toolbox for boosting fuel efficiency as well as driving performance. Among the others are direct fuel injection and camless valve actuation, which uses hydraulic or electrical actuators to precisely tailor the timing and degree of valve openings and closings to improve engine breathing.

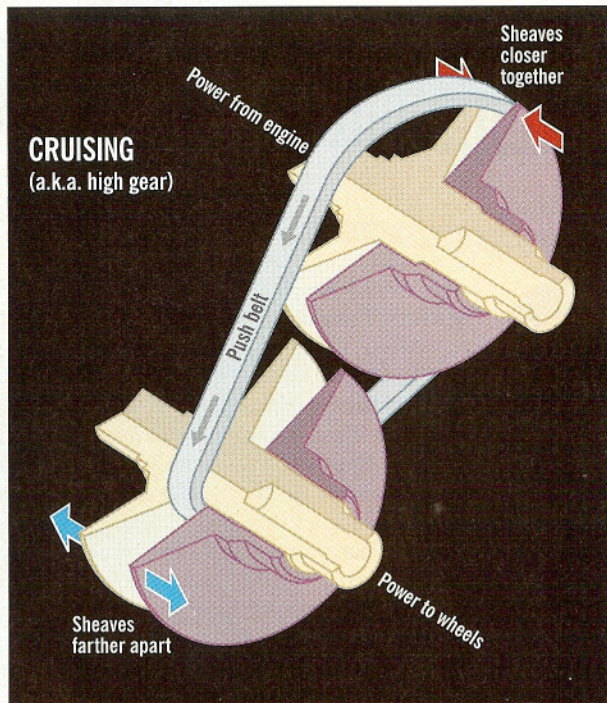
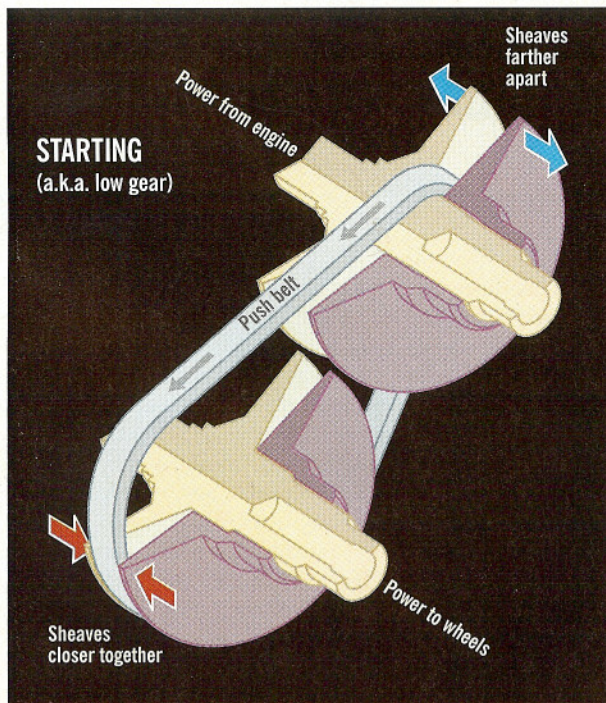
David Cole, director of the University of Michigan's Office for the Study of Automotive Transportation, reports that CVTs have shown up on the radar screen in his group's most recent survey of industry trends. "CVTs have a minimal presence today," Cole says, "but we project that by 2009 they will account for 7% of all passenger-car transmissions in the U.S., which would be about 560,000 units."

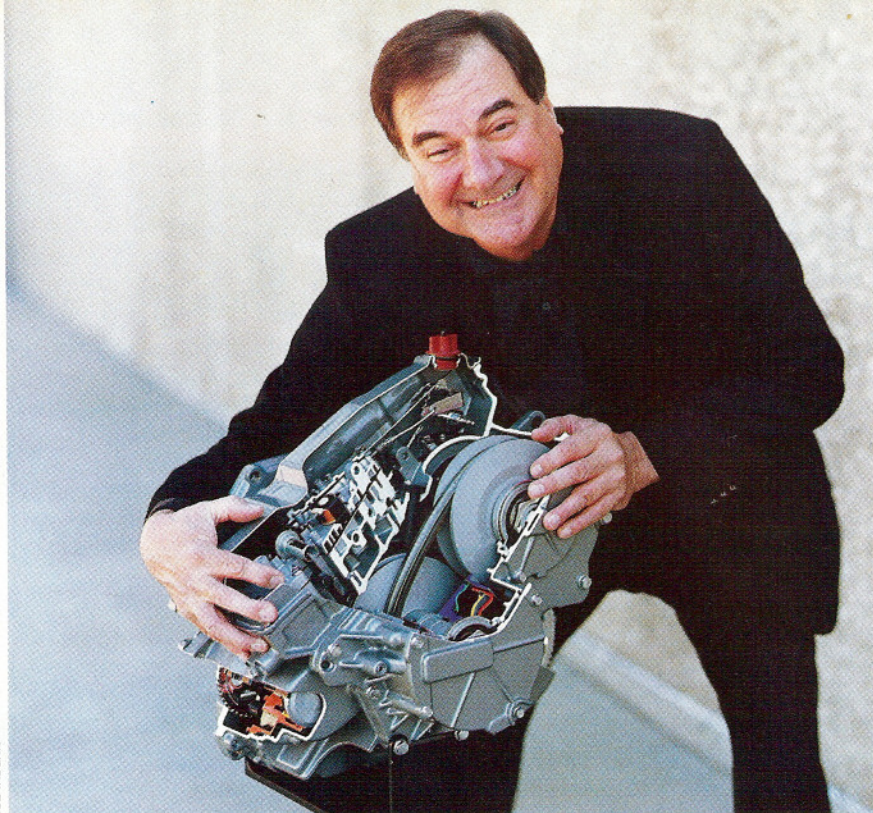
That estimate could turn out low. In a joint venture, Ford and the German transmission maker ZF are outfitting a plant in Ohio to crank out as many as a million CVTs a year by 2005. That doesn't count CVTs that GM will bring in from a plant in Hungary owned by its Opel subsidiary.

Shifting Without Gears

The transmission shown here replaces sets of toothed wheels with a sophisticated belt-and-pulley mechanism called a variator. The pulleys' tapered halves, or sheaves, slide close together or far apart, making possible infinite variations in the diameters the belt wraps around on each pulley. When the upper pulley's sheaves are far apart and the

lower sheaves are close together (left diagram), the effect is the equivalent of a small gear driving a large gear, as when a car is pulling away from a stop. Reversing the sheaves' positions (right) creates the equivalent of a high, cruising gear ratio. A key component is the unusual belt, which transmits power by pushing instead of pulling.





That's Arv Mueller, GM's powertrain boss, with the new Saturn transmission. It's a "really cost-effective way to get a big chunk of fuel economy," he says. "In this business, you'd kill for half a percent."

In Europe and Japan, where fuel prices have long been sky-high and drivers have shied away from automatic transmissions because they gulp more fuel, CVTs may catch on even faster.

If you have ever been aboard a snowmobile, you've experienced a CVT, perhaps without quite realizing what was going on. A snowmobile's rudimentary CVT consists of two pulleys connected by a stout rubber belt. One pulley is driven by the engine, and the other one drives the track mechanism that propels the sled forward. The tapered halves of the pulleys, known as sheaves, form a V-shaped notch that widens or narrows as you ride the snowmobile. This forces the belt to move closer or farther from the centers of the sheaves, effectively varying the diameters the belt wraps around.

As one pulley's diameter gets smaller and the other's gets bigger, or vice versa, the mechanical ratios between them shift in a seamless continuum. Like other simple, useful mechanisms that somebody else has perfected, the heart of a CVT looks right and obvious and makes you wonder, Why didn't I think of that?

CVTs were offered in little 1980s cars like the 73-horsepower Justy because the technology of the day couldn't handle the power output of bigger engines without going to pieces. But all that is changing. Engineers have learned to make CVTs that can survive in cars producing four

times that amount of power. Eventually they could outnumber today's automatics, which are sometimes called step-gear transmissions because of the rigid ratios defined by their three to five meshing sets of toothed gears.

Inventors since the days of the earliest automobiles have sweated over stepless transmission mechanisms that could connect the engine to the road through infinitely variable ratios. Today's prevalent belt-type CVT technology was developed by Dutch engineer Dr. Hub Van Doorne, whose company, Van Doorne's Transmissie, built a CVT called the Variomatic for the DAF, a small car that went into production in the Netherlands in 1958. The Variomatic's rubber V-belt sufficed to handle the modest 30hp output of the DAF's tiny 0.6-liter two-cylinder engine.

Van Doorne, in Tilburg, the Netherlands, was acquired in 1995 by Germany's Bosch Group and has become the Intel of the CVT world. Its belt-and-pulley set, called a variator, as well as its engineering expertise, are in almost all the belt-type CVTs built. The other significant CVT design is the quite different and costlier "toroidal" type offered by Nissan (see box).

This year Van Doorne expects to produce 430,000 of its ultra-tough CVT belts, ramping up to 1.5 million belts by 2005. They're currently used in CVT cars built by Fiat, Lancia, Rover, Honda, Mitsubishi,

Nissan, and Subaru. These highly engineered stainless-steel beauties are not the V-belt from your father's rototiller. As Van Doorne's engineers moved away from rubber belts and into more rugged metal designs, they dropped the convention of one pulley *pulling* the other via the belt, and hit upon the idea of a belt that *pushes*. It seems utterly counterintuitive at first, like pushing on a rope. But it works.

The mighty push belt is made up of hundreds of flat stamped-steel elements with notched edges through which run thin steel bands that hold them together to form a loop. The whole shiny thing looks like a trendy high-fashion necklace. As the CVT's driving pulley is turned by the engine, each element of the belt pushes against the next, transmitting torque to the driven pulley, which connects to the axles and wheels. By constantly pinching the belt with considerable hydraulic force regardless of how close or far apart they are, the sheaves keep the belt from developing slack or slipping on the pulleys, which would destroy the variator.

Van Doorne's patent portfolio bulges with metallurgic, heat-treating, and metal-forming wisdom gleaned during years of sticking with the tough challenge of making belts survive ever higher power levels. Elias van Wijk, the engineer in charge of the company's work with GM, says belts now in production can live with about 160 foot-pounds of torque (the output of a 150hp engine) and that heftier versions now in development should be able to handle up to 310 foot-pounds, which gets into full-sized pickup-truck territory.

An ironic aspect of U.S. automakers' interest in CVTs is that they aren't intended to fix something that's broke or banish a sales-destroying irritant from the product. On the contrary, American customers are generally quite content with their automatic transmissions. With a bit of luck, the approximately 500 parts inside one of these modern hydro-electro-mechanical wonders—compared with about 180 parts in a typical engine—will do their jobs without complaining for the life for the car.

This presents a challenge to the engineers at GM's powertrain division in Pontiac, Mich., who are working on the company's first CVT vehicle. They are struggling to make it perform in such a way that drivers will be largely unaware of anything different under the hood. They figure, Why tinker with success? GM is putting its first CVT into the

GOING GEARLESS

four-cylinder version of a 2002 Saturn SUV that will reach showrooms about 12 months from now. Judging by a drive in a "mule" test vehicle equipped with a development version of the SUV's 2.2-liter CVT powertrain, customers will be treated to quite a creamy-feeling experience, with no more noise than usual.

Still, the sensation is novel. When you step on the gas pedal with a conventional automatic, the vehicle pulls smoothly away and you feel slight surges in the power delivery as the transmission upshifts through its gears. Things feel different with a CVT, which holds the engine speed within a narrower range. There are none of those familiar engine-speed run-ups and abrupt slowdowns as an automatic transmission shifts gears; instead, the engine's revolutions per minute (rpms) just slide up and down somewhat as the vehicle accelerates and slows.

This absence of familiar automatic-shifting cues in the seat of the driver's pants can make a CVT car feel as though it's accelerating sort of slowly. But the speedometer says otherwise. Track tests prove that some CVT cars can outspurt even a hotshot driver working a manual five-speed transmission. One reason: There are no pauses in power delivery, which are unavoidable when traditional toothed gears are shifted.

While CVTs take a bit of getting used to, the engineers are doing a lot to make them endearing. The Saturn SUV will have upshift-downshift buttons on the steering wheel that drivers can tap when they're feeling nostalgic for the discrete gear ratios of yore. The CVT's control chip will respond by adjusting the pulley diameters to preset ratios stored in its memory. Otherwise the CVT will follow its own muse, selecting the most fuel-efficient ratio as conditions vary.

The fuel-efficiency gains that a CVT delivers come from improving the fluid dynamics of the engine's breathing. Gasoline engines inhale air through an intake manifold that contains a round, pivoting plate called a butterfly valve. Stepping on the gas pedal opens the plate, admitting more air, which the fuel-injection system complements with gasoline, causing the engine to rev up. At idle speed and at low throttle, however, the constriction caused by the narrow opening inhibits the air flow, causing what are called pumping losses. With its clever electronic control system, the CVT forever juggles gear ra-



The CVT-equipped Saturn SUV goes on sale next fall.

tios to let the engine run at wider, more efficient throttle openings where pumping losses go down, while keeping rpms relatively low to save fuel.

Part of the trick involves using a throttle-by-wire setup instead of a direct mechanical linkup between the driver's foot on the gas pedal and the throttle plate. A control chip, which considers various factors including engine speed, vehicle speed, and how far and abruptly the driver has pushed the gas pedal, instructs an electrical actuator that moves the

a comparable car with a traditional automatic transmission. There have even been rumors that Honda may roll out a CVT-equipped motorcycle, which would be something different indeed.

Every car has a mechanism known as a launch device to connect the engine's spinning crankshaft with the transmission. Honda's Civic HX uses the most fuel-efficient launch device, which is a multiplate clutch pack that disengages when the car comes to a stop and idles, then hooks back up again when the driver steps on the ac-

A CVT car can feel as though it's accelerating slowly. But some CVT cars can outspurt even a hotshot driver working a manual transmission.

plate. The CVT is yet another in a series of automobile control mechanisms that have benefited from today's cheap, smart microprocessors.

CVT control chips can be programmed with different "ratio maps" to suit the driver's mood. For example, when a rapid and deep push on the gas pedal signals that the driver wants to sprint, the chip consults a performance-ratio "map" in its memory that temporarily sacrifices efficiency for acceleration by letting the engine rev faster. Once at cruise speed, the chip reverts to a fuel-saving map. I drove a CVT-equipped Honda SUV called the HRV, which is sold in Japan and Europe. It has steering-wheel buttons that allow the driver to choose sport or cruise modes. They're fun to switch back and forth.

Americans who itch to get behind the wheel of a CVT car right now can head to a Honda dealer and ask if there's a Civic HX coupe in stock. There probably won't be, as the company hasn't promoted the HX very well. But it has a nicely engineered Van Doorne-belt CVT that made it the first automatic-transmission car on the EPA's list of top ten fuel-economy champs. The recently unveiled next-generation Civic line continues to include a CVT model, which costs \$200 more than

celerator. Karl Janovits, GM's chief CVT engineer, says he and his colleagues were willing to sacrifice a bit of fuel efficiency in exchange for a smoother launch from standstill than a clutch pack is able to deliver. Their launch device is the same type of torque converter used with conventional automatic transmissions.

To understand how a torque converter works, take a bagel and slice it the long way. Now scoop out the halves and put little dividers, or vanes, in them so they resemble circular ice-cube trays. That's what the two halves of a torque converter look like. In operation they face each other without touching in a bath of automatic transmission fluid, and as the driving half connected to the engine revs up, the swirling fluid drags along the driven half. This fluid-coupling device is the reason automatic-transmission vehicles have a slight forward creep at idle that Americans are fond of, as well as a creamy-feeling launch. GM thinks the CVT should feel the same way.

Aside from the progress Van Doorne has made with its belts and pulleys, the main development that's making CVTs viable today is a smart, fast electrohydraulic control system. Its key components are the microprocessor and a quiet-running, high-

pressure hydraulic pump that can generate the pulley-clamping forces needed to keep the belt from slipping. "Today the system can change ratios quickly and ensure the durability of the belt and sheaves, which just cannot be allowed to slip," says Karla Berger, GM's CVT calibration manager, who predicts, "We are going to have a zero-maintenance transmission."

Like all CVTs, it will also have an unusually broad range between the highest and lowest multiples of engine speed to wheel speed. This provides both a strong launch and low engine rpms at cruising speed to improve fuel economy. In GM's CVT, the multiple will vary by a factor of 5.9 to 1. That compares with ratios of only 4.3 to 1 and 5.1 to 1, respectively, in the company's four- and five-speed automatics.

Janovits, who has worked on CVT programs at GM since 1984, says that the belt-and-pulley variator sets, which Van Doorne will supply to the company's plant in Hungary, are fairly costly. The pulleys must be made from forged steel, he explains, which is then precision ground and heat-treated. Compared with GM's four-speed automatic, however, the CVT has 45% fewer parts, and Janovits expects it to cost no more initially than the older gearbox. With mass-production economies, he says, "it has the potential to get cheaper."

Mastering CVT manufacturing is topic No. 1 at ZF Batavia, the Ford-ZF joint venture near Cincinnati that's tooling up for production starting early in 2002. The 1.8-million-square-foot plant at Batavia, Ohio, is only half-occupied with machinery that produces four-speed automatic transmissions used in such Ford products as the Contour and Cougar, and in the Mazda 626. (The 1981-vintage factory's street address is 1981 Front Wheel Drive. Get it?) The unused space awaits \$500 million worth of new machine tools for making CVTs using Van Doorne belt-and-pulley sets. The plant will sell the transmissions to Ford and other automakers.

As CVT production ramps up in Batavia, traditional automatic-transmission building will wind down. Karl Kehr, ZF Batavia's chief financial officer and a former Ford guy, boldly predicts, "We believe that in eight to ten years there won't be a conventional automatic transmission on the market for front-drive ve-

In a plant near Cincinnati, a joint venture of Ford Motor and Germany's ZF is awaiting \$500 million worth of new machine tools for making CVTs.

hicles with less than 260 foot-pounds of engine torque," which means most front-wheel-drive vehicles. ZF engineers are refining the design of a belt-type CVT that can handle a maximum of 180 foot-pounds of torque, or roughly the output of a 2.5-liter V-6. A higher-torque model is also planned.

ZF's origins go back to Count Ferdinand Zeppelin of airship fame. (In German the letters stand not for "Zeppelin factory" but for "gear factory.") The company has long experience in making manual and conventional automatic transmissions; it has been working on CVT designs for a decade and owns a Belgian plant that produces a low-torque CVT used in a Rover vehicle. One of the tough tasks facing the engineers, Kehr says, is making sure the CVT can deal with the "back push" that occurs when a car towing a trailer crests a hill and begins descending. The CVT's controller has to be smart and quick enough to clamp down on the pulleys and avoid belt slippage that could finish off the pricey variator.

Ford managers won't reveal exactly where CVTs will first appear in their model lineup, but they are clearly itching to get the fuel-saving CAFE benefits. "We're excited about the technology, and we're in the process of a lot of development work to see what potential it has for some of our smaller front-drive vehicles," says Barbara Samardzich, chief engineer for automatic transmissions. "CVTs can

get us 6% to 10% better fuel economy, and they represent an evolution in shift quality that will enhance the driving experience."

From 1988 to 1997, Ford built a low-torque CVT in France called the CTX that was in about 200,000 small cars sold in Europe. "Like a lot of early CVTs, the CTX had basic hydraulic controls, and we're able to do a much better job of making smooth ratio changes now with electronic controls," says Craig Renneker, executive engineer for new automatic transmission programs. Like GM, Ford has chosen to use a torque converter as its launch device.

Van Doorne isn't totally without competition in CVT belts. Audi sells an A6 model in Europe that's equipped with a "multitronic" CVT that uses a proprietary, fierce-looking pull-chain made by LUK, a German driveline components maker. Audi says this A6, which is the highest-torque front-drive CVT car currently in production, may be exported to the U.S. next year. Its 2.8-liter V-6 engine produces 207 foot-pounds of torque. LUK's chain consists of several hundred thin steel plates connected with pins like a bicycle chain. The system's pulley sheaves actually squeeze the ends of the pins, which protrude beyond the plates. Audi brags that the chain wraps more tightly around the pulleys than a belt can, giving its CVT an unmatched ratio range.

Engineers familiar with Audi's CVT development program say it took a lot of sound-deadening material to suppress the LUK chain's whining sound, but the re-



The first CVT car, the tiny, Dutch-built DAF, was introduced in 1958.

sult is a sweet-driving system that's a benchmark for competitors. Its launch device is a multiplate clutch designed to deliver a slight amount of creep at a standstill, and there's a six-speed "manual" mode, like the Saturn SUV's, that allows the driver to control the timing of steplike gear changes.

The CVT has a head start in the latest

crop of fuel-saving technologies, with which it may later be combined. But to many auto executives, the CVT alone appears to offer a satisfactory payoff for now. "We have to decide where to spend our lunch money," says GM powertrain boss Mueller. "Camless valve actuation, direct fuel injection, and the CVT are three ways to improve efficiency, but the

CVT has the best return on investment." You can't add up the incremental fuel-saving benefits of these technologies without some losses, Mueller notes: "Six percent plus 6% plus 6% does not equal 18%. The total will be less, so we are starting with the highest-value system, which is the CVT." **F**

FEEDBACK: sbrown@fortunemail.com

Nissan's 'Toroidal' Approach

Not all continuously variable transmissions use a belt-and-pulley mechanism. Auto men have tinkered for years with "toroidal" mechanisms, so-called because their key functions take place in a doughnut-shaped internal space where rolling elements transmit power at variable ratios (see below). General Motors, using a Citroën design from the 1920s, had a fully developed toroidal CVT before World War II and continues to study the design for use in high-powered vehicles.

In Japan, Nissan sells two luxury cars, the Cedric and the Gloria, equipped with a toroidal CVT called the "Extroid."

by 10% when compared with a conventional automatic transmission. The Extroid's mechanism uses rotating, parallel disks with concave faces connected by pairs of "power rollers." When the engine is running, it spins the input disk, which turns the power rollers, which transmit the motion to the output disk and from there to the road.

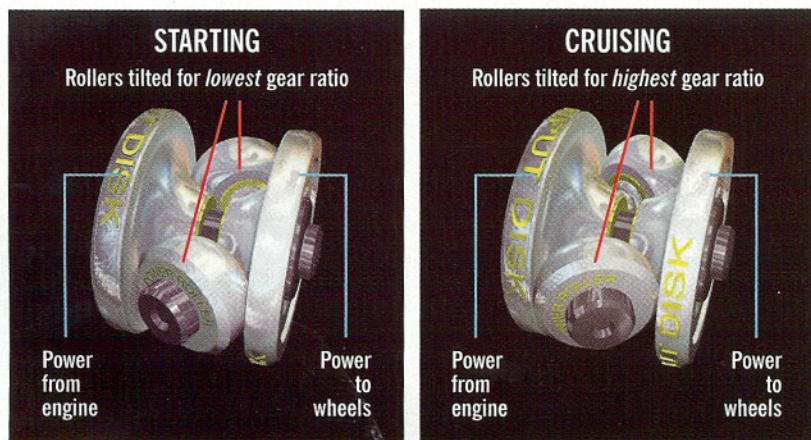
When the rollers swivel at different angles against the concave surfaces of the disks, which face each other, their points of contact produce varying multiples of engine speed to wheel speed. Thus, when one side of the power roller contacts the small-diameter area of the input disk,

the power roller's other side contacts the large-diameter area of the output disk. The result is a low startup ratio equivalent to a small gear driving a big one. The power rollers create a "high gear" effect at the opposite angle and can swivel to provide a smooth spectrum of ratios in between.

Engineering headaches have dogged the toroidal CVT's development. One of the biggest issues was coming up with metal disks and rollers that could withstand the three to ten tons of pressure at their points of contact. Nippon Steel, a bearing manufacturer whose metallurgists have long worked on toroidal CVT development, supplies the microfinished disk and roller components for the Extroid. They are made from a special steel alloy of unusually high purity into which

carbon is deeply infused to impart the required toughness.

Another major hurdle was coming up with a transmission fluid that could provide the metal-protecting benefits of oil, but without oil's slipperiness, which would render the disks and rollers incapable of transmitting torque. Idemitsu, another supplier, figured out the weird chemistry needed for what it calls "traction oil." This special sauce contains long-chain molecules with hooklike projections that interlock and become grippy when subjected to the extremely high pressures found at the disk-to-roller contact points.



This continuously variable transmission, available on two Nissan luxury cars sold in Japan, uses rollers instead of a belt. By tilting at different angles, they transmit power at varying ratios. At low speed, for example (left), the rollers' tilt creates the effect of a small gear driving a big gear. At a high cruising speed (right), a reverse tilt creates the opposite effect.

These real-wheel-drive cars have turbocharged V-6 engines that put out a hefty 285 foot-pounds of torque. Engineers who have driven the cars report that the novel CVT delivers power quite effectively to the asphalt. Says the University of Michigan's David Cole: "It's terrific, very smooth, responsive and quiet. I am particularly impressed with the power it can handle compared to other CVTs."

Jatco, the Japanese transmission maker, builds the Extroids for Nissan on a low-volume basis. They come as a \$2,500 option and, the company says, improve fuel economy