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Design of a Freeway-Capable Narrow Lane Vehicle*

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ABSTRACT

This study focuses on the design of a narrow (44 inches maximum width) vehicle capable of moving two occupants safely at freeway speeds with an emphasis on comfort, efficiency and performance. The design addresses consumer acceptance problems of past narrow vehicles such as "too small", "too ugly", "too unstable", "too wet", "too slow", "too complicated", and "too expensive". A full CAD model was developed to show the external vehicle shape, occupant seating and ergonomics, and the packaging of driveline components. Simulations were run using *SIMPLEV* and *Advisor 2002* to predict vehicle performance and range. The size and mass characteristics of the driveline components used in the simulations were based on commercially-available EV products and selected for the special requirements of a relatively lightweight (450-600 kg) vehicle. Dynamic stability and safety of the vehicle are of prime importance and were considered in all phases of the design.

The narrow lane "commuter" vehicle is designed to permit two cars to travel abreast on a standard lane, or single file on a shoulder or auxiliary lane of highway. The vehicle modeled incorporates electric drive and is designed to have a >100 mile range using lithium-ion batteries. This study shows that narrow lane vehicles using current technology power train components are a viable option to increase vehicle throughput on existing roadways and reduce transportation energy consumption.

*This work has been performed at the Institute of Transportation Studies, U.C. Davis and the Art Center College of Design in Pasadena, CA with partial funding from Jake Peters.

INTRODUCTION

MOTIVATION

"Advances are made by carrying out new combinations of old and sometimes new things." - Joseph A. Schumpeter, *the Theory of Economic Development, 1934.*

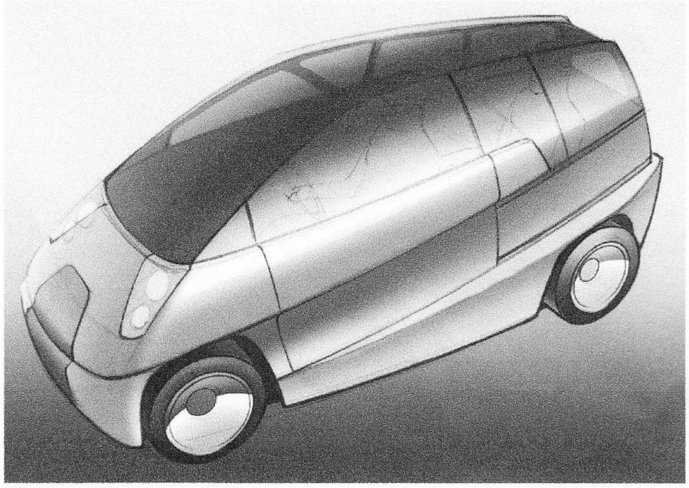


Figure 1

Previous studies by PATH (Partners for Advanced Highways and Transit) and others (1) have illuminated the need and viability for a class of smaller, lighter vehicles to complement existing vehicles and infrastructure. Innovative vehicles like this have been referred to as "Lean Machines", (2), "ultralight vehicles" (3), or "Narrow-Lane vehicles" (4). Although examples of vehicles of this type presently exist, none have been successfully marketed.

In the U.S., commuting is the single-largest component of overall vehicle miles traveled, 31.07% in 1995. The average vehicle occupancy in 1995 was 1.59 people per vehicle, but for commuting that figure was only 1.14. (5). Even though a full-size automobile is often grossly oversized for commuting, many citizens, view mass transit as an inferior alternative, and see as equally unsatisfactorily other transportation alternatives. By creating a new personal transportation system of narrow commuter vehicles and roadways, the American tradition of automobile use to provide effective personal mobility may be sustainably preserved (3).

As competition for land is increasing and the relative budgets for new roadways are decreasing, many regions are looking for options to maximize the utility of existing roadways. If integrated on existing roadways, narrow-lane vehicles could increase throughput by using dedicated or convertible half width lanes (6). Studies have also shown that widespread use of narrow vehicles would substantially reduce current transportation energy consumption and greenhouse gas emissions (7).

The benefits of widespread implementation of narrow-lane vehicles are then twofold: to increase the capacity of existing roadway infrastructure and to reduce transportation energy use and associated emissions . If such vehicles could provide the level of utility, comfort, and convenience that consumers demand, they would not feel deprived when driving them, and would not miss their full-size car or truck. Furthermore, if the commuter's average travel time (or perhaps as importantly, the standard deviation in commuting travel time) could be reduced, some consumers might ascribe significant incremental value to a narrow vehicle.

"Expanding the transportation options to include significantly smaller, energy-efficient vehicles provides an automobile-oriented solution to an automobile-oriented problem" (4) Thus, the motivation behind this design study is to provide an attractive alternative for consumers which could start the movement toward this new class of vehicles.

EXAMPLES OF NARROW-LANE VEHICLES

For the purposes of this study narrow-lane vehicles (NLV) are designated as freeway-capable vehicles designed primarily for commuting and having a reduced tread width. To reduce congestion on existing roadways narrow-lane "commuter" vehicles have been proposed to travel two abreast on a standard lane (re-striped) or single file on a shoulder or auxiliary lane of highway (6). There have been attempts to design and build smaller purpose-built commuter vehicles which do not conform to any existing vehicle class. The BMW Isetta and Messerschmitt KR 200 (figure 2), perhaps the earliest "commuter cars", were successful largely because of their low purchase price and operating costs. Table 1 summarizes some examples of prototype and production all-weather commuter vehicles.

Figure 2 - Messerschmitt KR 200

Table 1 – Examples of All-Weather Narrow Vehicles

Vehicle (bold indicates production vehicle)	Manufacturer	Number of wheels	Width (in)	Power Train	Passenger Capacity	Curb weight (kg)	Stability	Top speed (mph)
Luciole (1997)	Nat'l Inst. of Environmental Studies, Japan	4	47	BEV	2	910	good	93
Lean Machine (1982)	GM	3	36	ICE/si	1	160	excellent	80
Carver	**Vandenbrink**	3	51	ICE/si	2	620	excellent	111
City-el	**Elektromobil**	3	42	EV	1	290	poor	25
1L (2002)	VW	4	49	Diesel	2	267	good	70
Think City	**Ford**	4	63	BEV	2	960	good	56
Tango	Commuter Cars	4	39	BEV	2	1,386	good	124
Micro Max	**Covco**	3	39	BEV	2	300	good	42
KR 200	Messerschmitt	3	48	ICE/si	2	230	good	75
Sparrow	**Corbin**	3	48	BEV	1	613	good	70

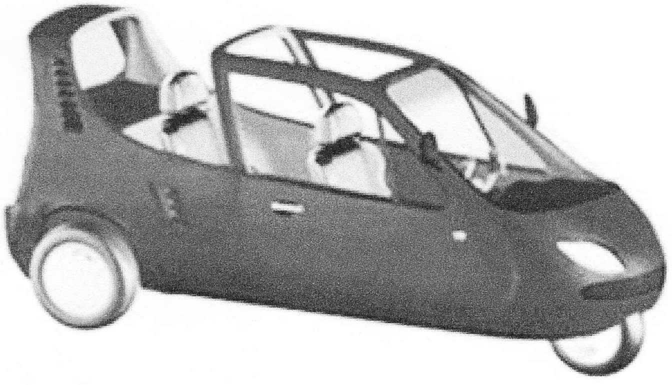


Figure 3 - Covco Micro Max

Figure 4 - VW 1L

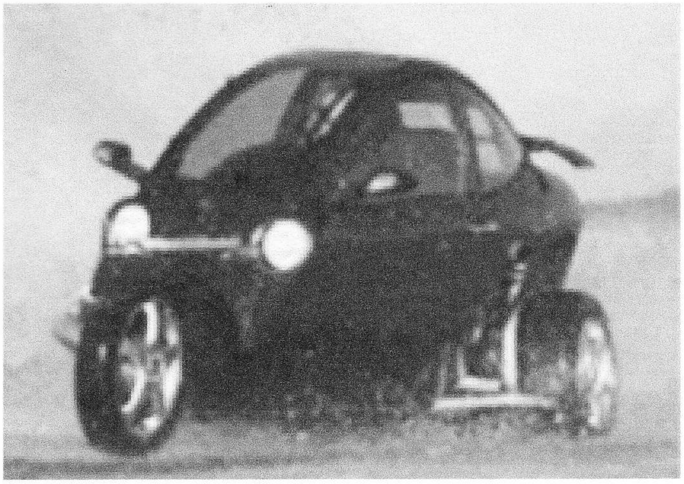


Figure 5 – Vandenbrink Carver

Although innovative, none of the NLV examples cited appear to be up to the task of wooing significant numbers of consumers from their present vehicles:

- The eccentric-looking, all-electric Corbin Sparrow commuter car may be the closest to an American-built success story. Until Corbin's recent bankruptcy, this vehicle developed a small following even though it could carry only one passenger and had a very short range (~25 miles).
- The nimble and freeway capable Dutch-made Vandenbrink *Carver* is intriguing albeit expensive at >$40,000. Using active-tilt, it automatically leans into turns like a motorcycle. This makes for an exciting, if somewhat unconventional ride.
- The 70+ mph, lightweight *VW 1L* is non-tilting but has good stability due to a low center of gravity. It also has very low energy consumption due to an advanced diesel power plant. Unfortunately this one-off prototype uses exotic materials and construction techniques that are not suitable for low cost production vehicles.
- The *Tango* is very narrow and gets its stability from many batteries mounted very low. This vehicle seems confused about its mission: It is short and narrow like an ultralight car but is performance biased and very heavy at 3,050 pounds.
- The Ford *Think City* is not a narrow car but a good example of an almost freeway-capable small production electric car. This discontinued Norwegian-designed production vehicle utilized Nickel Metal Hydride (NiMH) batteries, with an aluminum structure and plastic body shell.
- The Elektromobil *City el* is currently in use and had a failed introduction in the United States. This low-speed commuter vehicle is narrow but has, only one passenger capacity, and is not freeway capable partly due to poor stability at higher speeds.

SCOPE OF THS STUDY

The objective of this project is to design a NLV that would be attractive to a reasonable fraction of commuters. The NLV would need to feel safe and comfortable while driving in freeway traffic. A CAD (Computer Aided Design) model is used to show packaging details. The design is intended to meet the criteria and performance targets thought to be needed to attract a reasonably large market. The performance characteristics of the proposed design are projected using computer simulations and other analysis tools. This phase of the project is a "paper design" only, thus no hardware was constructed. Test data from commercially-available components are used as a basis for simulations to predict the vehicle performance characteristics. Wherever possible, actual components are specified. Where data for actual components are not available, data from commercially-available components are scaled up or down for use in simulations.

APPROACH/METHODOLOGY

An optimal design will meet all specified criteria including performance, stability, and safety while maximizing user comfort and efficiency. An integrated, iterative design approach was used since all vehicle design characteristics are interdependent. For example, a particular drive train component choice affects weight, weight affects stability, and stability affects safety. Thus, as design details were refined, each previous analysis was revaluated and if needed, simulations re-run. The following steps were used by the NLV Design Team to optimize the design:

- Establish design criteria
- Establish performance requirements
- Perform simulation/analysis
- Review results
- Repeat

Simulations

After basic specifications such as curb weight, frontal area, and drag coefficient were established for our narrow-lane vehicle, "SIMPLEV" and "Advisor" simulations were performed to confirm the size characteristics of the major drive train components such as motor and batteries, to meet the performance criteria. Vehicle efficiency/energy use was iteratively optimized using the design criteria and performance targets as constraints. The key results from the simulations were the performance and energy consumption. The vehicle ranges on the CYC-UDDS (U.S. federal urban driving cycle) and the CYC-FWFET (U.S. federal highway driving cycle) were determined by running successive cycles until the batteries were depleted.

To establish vehicle packaging, components specified from simulations were integrated into an "Inventor" CAD model. This model was used to optimize interior space and ergonomics, minimize frontal area, and calculate weight and center-of-gravity (CG) location. The optimum final shape will house the drive train and accessories, occupants and cargo and have low aerodynamic drag. The CAD model developed for packaging was used to determine the constraints for the outside body shape, which was rendered using the "ALIAS" CAD program. The ¼ scale model will be constructed from high-density rigid foam at the rapid prototyping lab at the Art Center College of Design in Pasadena, CA.

DESIGN CONSIDERATIONS

DESIGN CONCEPT

The NLV concept proposed in this study shares many of the attributes of previous small commuter cars such as the "Lean Machines" referred to by Garrison and Pitstick (2) and the ultralight vehicle described in NUCAR (3), but it differs in some important ways. Although having a narrower footprint than a conventional vehicle, our NLV is designed to have a similar driving experience to current production automobiles. Thus, the emphasis is not on minimum weight, cost, energy consumption and emissions but reduced weight, cost, energy consumption and emissions. This allowed us the freedom to design a vehicle more palatable to the average commuter than previous designs. This NLV concept is an all-weather, full-function, highway-capable vehicle that is intended to be deemed acceptable by a reasonable fraction of commuters.

DESIGN CRITERIA

Track Width

A maximum vehicle width of 44 inches was specified to allow the vehicle to operate in a narrow auxiliary lane, specified as a design constraint. For maximum stability (resistance to rollover) the widest possible tread width (tire center-to-center distance) for the available width is utilized. Thus, if a wider auxiliary lane were available, the minimum tread width could be increased. The effect of tread width on stability for our NLV is considered later in the paper

Please note, however, that if this NLV concept were equipped with automated guidance technology, a narrow vehicle could be operated in an auxiliary lane only inches wider than the vehicle (3). Thus, an NLV equipped with such guidance technology could possibly be designed with increased width, and thereby increased stability, while still achieving a design goal of two NLVs per standard highway lane.

Furthermore, if the NLV utilized active-tilt (8), stability would be improved although this creates issues regarding consumer acceptance.

Performance

Since the NLV is designed to be used on all roadways, performance characteristics such as acceleration, top speed, and grade ability need to be comparable to current production automobiles. Table 2 summarizes the major performance targets used in this study.

Table 2 – Performance Design Criteria

Acceleration: 0-60 mph	10-12 sec
Minimum range (electric):	100 miles
Minimum top speed	75 mph
Minimum grade ability:	6% @ 55mph
Maximum energy use from battery (City cycle)	100 (Wh/mi)

POWER TRAIN OPTIONS

This NLV design concept is not based on a particular drive train technology. Thus the drive line could be ICE, Battery Electric, or hybrid/electric/ICE. Battery and motor technology for electric vehicles has advanced significantly in recent years with some production examples such as the GM EV-1, Ford Think city, Honda EV Plus, Toyota E-Com, and Nissan Hypermini and Altra EVs. Our initial design study utilizes a battery/electric drive for the following reasons: 1) ease of packaging, 2) ease of prototyping, and 3) zero tailpipe emissions. It should be noted that BEVs still have issues regarding increased weight, recharge time, range, and battery cost and lifetime.

LAYOUT AND PACKAGING

Four Wheels vs. Three Wheels

When making a narrow vehicle there are many good arguments for a three-wheeled design. Three-wheels can lead to a more aerodynamic shape and lower weight due to fewer components. These vehicles are often classified as motorcycles thus bypassing standard automobile safety and emission regulations. In general, three-wheeled vehicles are less stable than four wheeled vehicles and many consumers are not attracted to their inherently unconventional appearance. Narrow three-wheeled vehicles utilizing active tilt such as the Vandenbrink *Carver* and GM "Lean Machine" are stable and highly maneuverable (8) but have added cost and complexity and may require some special skill to operate them. In an effort to create a narrow vehicle that has an appearance and driving feel similar to current production vehicles (albeit narrower), and keep cost and complexity at a minimum, this study chose a four-wheeled non-tilting narrow platform that relies on a low center of gravity for stability.

Front drive vs. Rear Drive

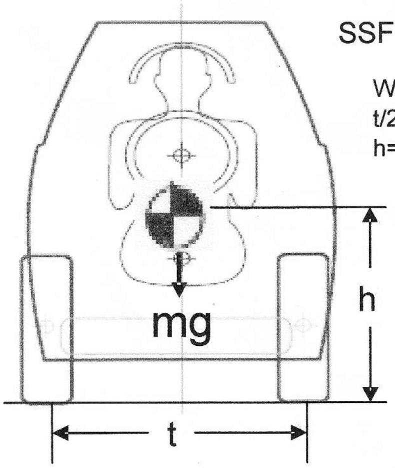
To optimize packaging efficiency and minimize cost, only front motor/front drive and rear motor/rear drive configurations were considered. Since a front weight biased, front drive layout offers predictable, inherently under steering handling characteristics in vehicles such as this NLV concept (9), it was the choice for this study.

Suspension/Brakes/Steering

Four-wheel disc brakes with ABS (Anti Lock Brakes) were specified for maximum stopping power and minimum weight. In addition, the ABS hardware (sensors, processor, etc.) would be compatible with ASC (active stability control) if it was employed. A conventional fully-independent control arm/McPherson strut set up was specified to save weight and cost and provide minimum intrusion into the passenger compartment and battery storage area. A rack-in-pinion steer-by-wire system was specified to facilitate packaging and reduce weight.

STABILTY

One of the key challenges of this project was to design a relatively narrow conventional four-wheeled vehicle which would be acceptably stable. Thus, once weight and CG height were calculated, a static stability analysis was performed to predict the vehicle's inherent resistance to rollover as in figure 6 below (10). A static stability factor (SSF) or "rollover threshold" was determined for this NLV concept which could be directly compared to published data for existing passenger vehicles and light trucks from NHTSA (National Highway Traffic Safety Administration) (11). In addition to the SSF, real world dynamic stability depends on many other factors such as roll stiffness, suspension geometry, and weight distribution (4). Although even vehicles with a high SSF can rollover under some conditions, the SSF is a good indicator of a vehicle's likelihood to rollover.



$SSF = (t/2)/h$

Where
$t/2$= Half tread width
h= CG Height

Figure 6

NHSTA found that the Rollover Resistance Ratings and the SSF ratings related very closely to the real-world rollover experience of vehicles in a study of 220,000 actual single vehicle accidents (11). Since dynamic stability is difficult to predict without an actual test vehicle, the SSF was used as a starting point for purposes of comparison for the NLV model with other passenger cars. Typical NHTSA published SSF values range from 1.5 for a large sedan or sports car to 1.0 for a less-stable sports utility vehicle with a high CG (see table 7).

SAFETY

It is commonly believed that large, heavy vehicles fair better in accidents than lighter, small vehicles. This is surely the case unless special consideration is given to safety in the lighter smaller vehicle (4). Since this NLV concept is designed to operate at highway speeds and has substantially lower mass than current productions cars, crashworthiness is a major area of concern in its design. Daimler Chrysler addressed this problem when designing their ~1000 kg Mercedes Benz A-class sub-compact car. By incorporating features such strategic placement of crush zones and major drive train components, front and side air bags, seatbelt pretensioners, and a passenger safety cell, the A-class has a four star crash rating equal to heavier vehicles (12). To this end, these same considerations will be incorporated in the design of this NLV concept. A minimum of 20 inches of crush space was allowed for (front and rear) and a rigid passenger "safety cell" to protect the occupants was incorporated into the design structure. Additional passenger restraint will be considered in future work.

PROPOSED DESIGN

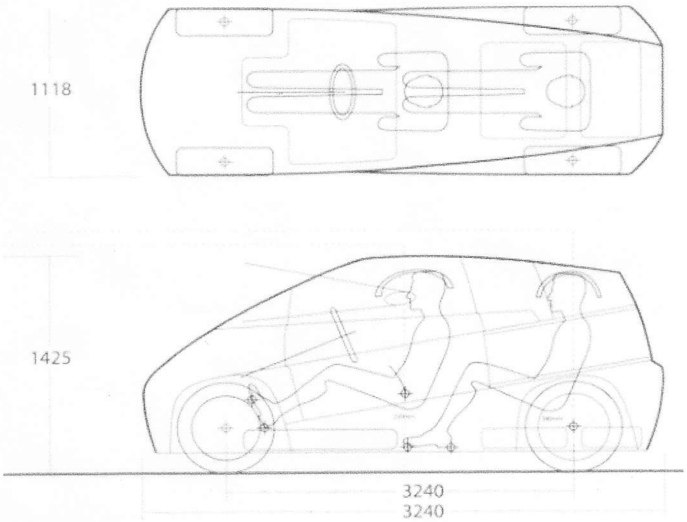


Figure 7

AESTHETICS and ERGONOMICS

The primary focus in designing the vehicle exterior was to meet the basic dimensional criteria and packaging constraints. To keep the vehicle narrow, a tandem seating arrangement with under-floor mounted batteries was chosen. The final package presents a good compromise between interior space, occupant comfort, storage, ingress/egress, stability, and low frontal area.

The occupants are placed as low as possible while maintaining a conventional seating position and good outward visibility. The target for seating height and position was that of a 2003 Honda Accord. The vehicle height was kept as low as practical for reasons of aesthetics as well as stability. The tires and wheels were given a larger exterior presence, to improve the stance and visual impact of the vehicle

The styling is contingent on the vehicle's mission. A tapered body improves the aerodynamics as well as defines the vehicle's form. One innovative feature integrated into the design is the use of sliding doors. They serve to allow easy ingress/egress, while using outside space more efficiently than a typical two-door vehicle. These primary features and the dynamic angle they create drive the exterior styling. The "one-box" form is the most cohesive way to combine these elements in such a small vehicle, and tends to reflect the progressive, urban environment it is designed for.

AERODYNAMICS

The shape of the NLV concept vehicle is somewhat tall and narrow with a similar profile to modern minivans (see figure 1). Other aerodynamic considerations include flush mounted glass and headlights and a smooth under-belly as well as the absence of large radiator cooling ducts. Thus, the drag coefficient is estimated to be slightly lower than that of a "slippery" minivan, such as the European VW Sharon which has a Cd of approximately .31 (13). Hence, an estimated Cd number of .30 was used in our simulations.

PACKAGING

In Figure 8 is the CAD model of this NLV concept and illustrates the location of the major components. To maximize this NLV concept's resistance to rollover, vehicle height was kept at a minimum and major drive train components were placed as low as possible. By placing the battery packs under the floor, traditional driver visibility, seating height and comfort were retained while keeping the CG low. The battery pack was divided in two to allow space for the rear passenger's feet and to keep the roofline low. The figures below show the packaging of major components such as motor, batteries, suspension, passengers, crush space, and body structure.

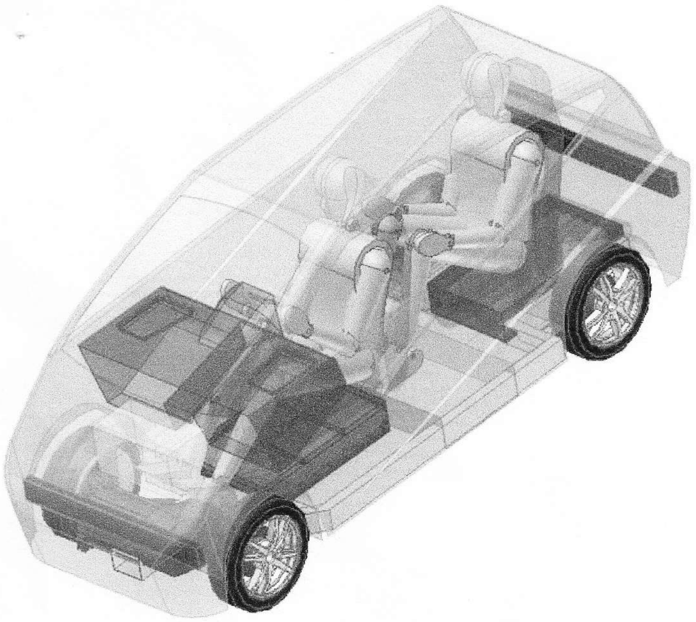


Figure 8

Vehicle Specifications

The general vehicle specifications used for the simulations are in table 3 below.

Table 3 - Vehicle Specifications

General	
Width:	1.12 m (44")
Track width	1.12 m (44")
Overall length	3.24 m (128")
Height:	1.43 m (56")
Seating	2 Passengers, tandem
Ground clearance:	.152 m (6")
Curb weight:	550 kg (1,210 lb)
Max payload:	136 kg (300 lb)
Frontal area:	1.35 m^2 (14.5 ft^2)
Cd:	.30
Rolling resistance	.006
Wheels	
Number	4
Size (radius)	13 inch
Outer Tire diameter	.28 m
Type	Aluminum
Driven wheels	Front

Safety and Convenience Accessories

A list of safety and convenience accessories are listed in table 4.

Table 4 – Passenger Safety & Convenience

Air bags	1 Front, 2 side
Power steering	No
Power windows	Yes
Stability assist	ABS, Stability control
Visual aides	Video cameras or high-mounted rear-view mirrors
Heating	Yes
Air conditioning	Yes

VEHICLE AND COMPONENT CHARACTERISTICS

Drive Train

This NLV concept utilizes high-energy SAFT 82 Ahr batteries (14). A Solectria (15) 35 kW motor was chosen for its high efficiency and durability. The drive train layout can be seen in figure 8. Table 5 summarizes the component characteristics.

Table 5 – Drive Train Specifications

Battery	
Battery type	Lithium ion
Battery manufacturer	Saft
Battery management system	yes
Temperature management	Liquid cooled
Energy density for module (Wh/kg)	116
Battery wt with packaging (kg)	97 kg
Total battery capacity	13.1 kW hours
Voltage	160
Capacity (Ahr)	82
Motor	
Motor type	Single AC induction
Motor size	35 kW
Motor manufacturer	Solectria
Motor max efficiency	92%
Transaxle	Mechanical differential

PROJECTED VEHICLE PERFORMANCE AND STABILITY

Performance

Table 6 summarizes the results from the *SIMPLEV* simulations based on the narrow-lane electric vehicle model with the specifications described above.

Table 6 - Performance

Acceleration: 0-60 mph	12 sec
Range (CYC-UDDS)	182 km (113 miles)
Range (CYC-FWFET)	211 km (131 miles)
Top speed	137 km/h (85 mph)
Grade ability:	6% @ 89 km/h (55 mph)

Stability Results

Based on the weight and CG location derived from the CAD model a SSF was determined for the NLV. Even with its narrow width, the SSF of this NLV concept is within the range of vehicles currently sold in the United States. The SSF is comparable to current production minivans and SUVs such as the Toyota Sienna and Lexus RX 300. Table 7 compares the SSF of the NLV with other production vehicles.

Table 7 – Static Stability Comparison

VEHICLE(2002 model year)	SSF (Track =44 in)
NLV	**1.25**
Toyota Sienna Minivan	1.25
Jeep Cherokee classic	1.08
Toyota Echo	1.32
Lexus RX 300 SUV	1.20
Honda Accord	1.45

If equipped with "active ride height" the vehicle could be automatically lowered (1-2 inches) at freeway speeds. This would effectively raise the SSF but would add cost and complexity. For example, calculations based on the NVT model show lowering the ride height of our NLV model 2 inches, would result in a SSF increase from 1.25 to 1.44. Table 8 shows the results ground clearance vs. SSF.

Table 8 - Ride Height Sensitivity

GROUND CLEARANCE (in)	SSF (track=44 in)
6	**1.25**
5	1.34
4	1.44

As previously mentioned any increase in track width will increase the resistance to rollover. Table 9 shows the results for track width vs. SSF for selected track widths.

Table 9 – Track Width Sensitivity

TRACK WIDTH (in)	SSF (Ride height =6')
40	1.12
42	1.19
44	**1.25**
46	1.32
50	1.45

PROJECTED ENERGY USE

Table 10 summarizes the energy use for this NLV concept predicted from *SIMPLEV*. These are only for the vehicle and do not include the loss from an off-board in battery charger. The CYC-UDDS is the U.S. federal urban driving cycle and the CYC-FWFET is the U.S. federal highway driving cycle.

Table 10 – Energy Consumption

Energy use from battery (CYC-UDDS)	100 Wh/mile
Energy use from battery (CYC-FWFET)	90 Wh/mile

FUTURE WORK

Future work for the NLV concept vehicle will be to demonstrate the viability of a vehicle of this type on public roads. This will include:

- Detailed design
    - Refined models
    - Simulation verification
- Construction of a working prototype at U.C. Davis
- Evaluation of the prototype for:
    - Performance
    - Aerodynamics
    - Stability
- Public demonstration:
  Demonstrate concept vehicle on dedicated lane incorporating IVHS technology

SUMMARY AND CONCLUSIONS

From this design study it is clear that an attractive, functional, Narrow-Lane vehicle is possible. A combination of recent technology such as high energy batteries, high-efficiency motors and controllers, stability control, active ride height (not used herein) make this possible. The NLV concept presented here by the U.C. Davis Narrow Vehicle Team is a potentially safe, attractive, vehicle with acceptable performance, and low energy use and emissions.

Results from the study indicate that a conventional four-wheeled platform could be sufficiently stable if the right measures (such as low CG height, low ride height, and active stability control) are employed.

Previous studies also support the role vehicles of this type could play in reducing congestion on existing roadways by increasing vehicle throughput as well as reducing transportation energy use and greenhouse gas emissions.

Integration of narrow-lane vehicles into the existing fleet will take forward thinking by many different constituencies: Vehicle designers and manufacturers will have to offer attractive vehicles that are not prohibitively expensive; consumers will have to be open to new experiences and technologies; policy makers (including the highway department) will have to stray from the status quo and consider such concepts as potential mitigants to our present commuting woes and possible future energy cost and availability problems.

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